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Comparison of Energy-Related Carbon Dioxide Emissions Intensity of the International Iron and Steel Industry: *Case Studies from China, Germany, Mexico, and the United States*

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Abstract

Production of iron and steel is an energy-intensive manufacturing process. The energy efficiency of steel production has a direct impact on overall energy consumption and related carbon dioxide (CO_2) emissions. The goal of this study was to develop a methodology for accurately comparing the energy-related CO_2 emissions intensity of steel production in different countries and to demonstrate the application of this methodology in an analysis of the steel industry in China, Germany, Mexico, and the U.S. Emissions intensity values are often sought by policy makers who must decide questions related to energy, greenhouse gases, and competitiveness. Our methodology addresses the industry's boundary definition, conversion factors, and industry structure. The results of our analysis show that, for the entire iron and steel production process, the base-case (2010) CO_2 emissions intensity was 2,148 kilogram (kg) CO_2/tonne crude steel in China, 1,708 kg CO_2/tonne crude steel in Germany, 1,080 kg CO_2/tonne crude steel in Mexico, and 1,736 kg CO_2/tonne crude steel in the U.S. One of the main reasons that Mexico has the lowest CO_2 emissions intensity is Mexico's large share of steel production using electric arc furnaces (EAFs) (69.4%). EAF steel production has lower CO_2 emissions intensity than production using blast furnaces/basic oxygen furnaces. China, by contrast, has the smallest share of EAF production among the four countries – 9.8% in the base-case year 2010. In one scenario, we applied the Chinese share of EAF production to the other three case-study countries; the result was an increase in CO_2 emissions intensity of steel production of 19% (2,036 kgCO_2/tonne crude steel) in Germany, 92% (2,074 kgCO_2/tonne crude steel) in Mexico, and 56% (2,703 kgCO_2/tonne crude steel) in the U.S. compared to these countries' base-case analyses. In another scenario, we applied the Chinese national average grid electricity CO_2 emissions factor from 2010, which is the highest emissions factor among the four countries, to the other three countries. In that scenario, the CO_2 emissions intensity of steel production increased by 5% in Germany, 11% in Mexico, and 10% in the U.S. Additional scenarios were analyzed showing that when comparing the CO_2 emissions intensities of the steel industry in different countries, it is necessary to take into account the industry structure, especially the share of EAFs and the effect of electricity grid CO_2 emissions factors. This report also discusses a number of other important variables affecting steel industry CO_2 intensity.

Content

Acronyms

BF	blast furnace
BOF	basic oxygen furnace
CDQ	coke dry quenching
CO_2	carbon dioxide
DRI	direct-reduced iron
EAF	electric arc furnace
EIA	Energy Information Administration (U.S. Department of Energy)
ETS	Emissions Trading System
EU	European Union
GHG	greenhouse gas
GJ	gigajoule
IEA	International Energy Agency
IPCC	Intergovernmental Panel Climate Change
kg	kilogram
MJ	megajoule
Mt	million metric tonne
NAICS	North American Industry Classification System
NCV	net calorific value
TRT	top-pressure recovery turbine
worldsteel	World Steel Association
WRI/WBCSD	World Resources Institute/World Business Council on Sustainable Development

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1. Introduction

Iron and steel production is an energy and carbon dioxide (CO_2) intensive manufacturing process. In the four countries investigated in this report, two types of steel production dominate: blast furnace/basic oxygen furnace (BF/BOF) and electric arc furnace (EAF) production. BF/BOF production uses iron ore to produce steel. The reduction of iron ore to iron in a BF is the most energy-intensive process within the steel industry. EAF production re-melts scrap to produce steel. BF/BOF production is more energy intensive and emits more CO_2 than EAF production (Aichinger and Steffen 2006).

This report describes a follow-up study to Hasanbeigi et al. (2011). In the 2011 report, we compared the energy intensity of steel production in China and the U.S. In the current report, we have modified the methodology developed for the previous report so that we can now compare the energy-related CO_2 emissions intensity of the iron and steel industry in four countries: China, Germany, Mexico, and the U.S.

As Tanaka (2008) pointed out, "energy consumption and energy intensity are often estimated based on different definitions of an industry's boundaries, making comparison at best difficult, at worst invalid." The goal of this updated study is to modify the methodology developed in our previous study so that we can use it to accurately compare the CO_2 intensity (CO_2 emissions per unit of crude steel produced) of steel production in China, Germany, Mexico, and the U.S. Our methodology provides boundary definitions, conversion factors, and physical-versus-economic CO_2 intensity indicators to develop a common framework for comparing steel industry CO_2 emissions in these four countries. More details about the data sources, data preparation, and assumptions used in the current study are described in Hasanbeigi et al. (2011) and Appendices 1 and 2 to this report.

Previous comparisons of international steel industry energy use and energy or CO_2 intensity have employed a range of methods. Worrell et al. (1997) found that physical indicators of steel sector energy and CO_2 intensity provided a more robust basis for comparison among countries than economic indicators. Within the range of analyses based on physical factors, a variety of study boundaries, units of analysis, and conversion factors have been used. For example, Worrell et al. (1997) use crude steel production as their unit of analysis whereas Stubbles (2000) calculated energy use and CO_2 intensity per ton of shipped steel. Likewise, whereas Andersen and Hyman (2001) include coke-making energy use, Kim and Worrell (2002) omit coke making from their respective definitions of the industry boundary.

A review of comparison studies shows that boundary and conversion factor assumptions are not always explicitly stated and appear to vary widely, especially for characterizing imported or off-site produced inputs. Consensus has yet to form on boundaries and conversion factors for comparison of international steel production CO_2 intensity, resulting different studies producing widely disparate results that are difficult to interpret and compare. For example, Tanaka (2008) presents a case study on Japan's iron and steel industry that illustrates the critical role of proper boundary definitions for a meaningful comparison of CO_2 intensity for the steel industry. Depending on the boundaries set for the analysis, the energy use per tonne of crude steel that Tanaka calculated ranges from 16 to 21 gigajoules (GJ), which results in similar variation in CO_2 intensity. In addition, Farla and Blok (2001) studied the data for physical-energy and CO_2-intensity indicators in the steel industry and found mistakes in reported energy data, which make reliable international comparisons of countries even more difficult. Furthermore, different international greenhouse gas (GHG) accounting and reporting frameworks have set different boundaries for the iron and steel industry. Figure 1 shows the different boundary definitions in international guidelines for GHG emissions of BF integrated steel plants (Tanaka 2008). It is clear that CO_2 intensity calculated using different guidelines – Intergovernmental Panel Climate Change (IPCC), European Union (EU) Emissions Trading System (ETS), or World Resources Institute/World Business Council on Sustainable Development (WRI/WBCSD) – cannot be compared to one another.

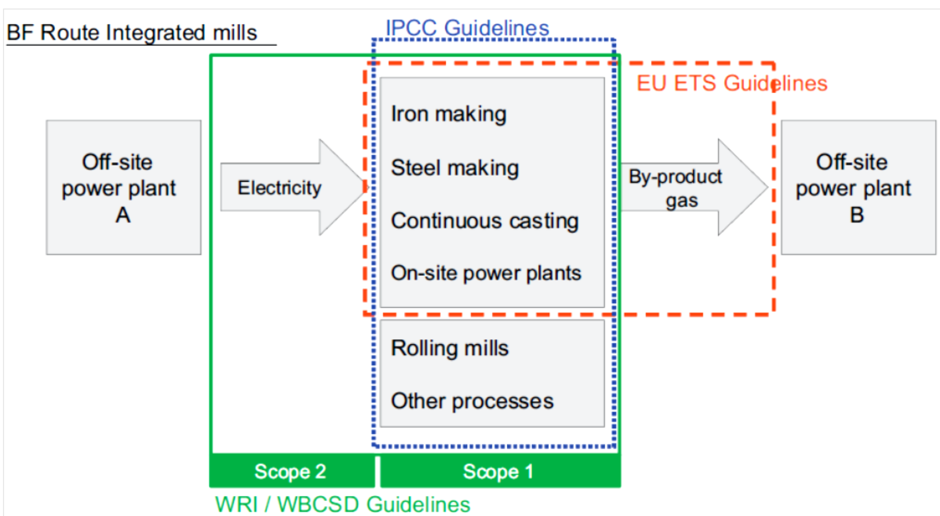

Figure 1. Different boundary definitions in international guidelines for calculating GHG emissions of BF integrated steel plants (Tanaka 2008)

Policy makers often seek a single CO_2 intensity value for steel production in individual countries to aid in decision-making related to GHGs and competitiveness. However, it is difficult to provide a single CO_2 intensity value for steel production in an individual country that can then be used to compare CO_2 intensity among countries. The above analysis illustrates that such a single indicator does not provide enough information to fully explain country-specific conditions.

2. Overview of the iron and steel industry in China, Germany, Mexico, and the U.S.

2.1. The iron and steel industry in China

China is a developing country currently in the process of industrialization. The Chinese iron and steel industry has grown rapidly along with the national economy. In 1996, China's crude steel production surpassed 100 million metric tonnes (Mt). Since then, steel production in China has continued to increase rapidly, and for 14 continuous years China has been the world's largest crude steel producer. The average annual growth rate of crude steel production was 18.5% between 2000 and 2009. Steel production in 2010 was 637 Mt (worldsteel 2013), representing 46.6% of world production that year. China's steel industry is a significant contributor to global CO_2 emissions.

2.2. The iron and steel industry in Germany

Germany's crude steel production increased from 38 Mt in1990 to a peak of 48 Mt in 2007, after which production dropped to 44 Mt in 2010 (worldsteel 2013). The increase was the result of increasing production of steel in EAFs while production using the BF/BOF process remained almost constant at an annual total of approximately 30 Mt of hot metal (WV Stahl 2013). The German iron and steel industry has continuously reduced its consumption of coke in the BF by 50% over the last six decades by employing efficiency measures such as top pressure recovery turbine (TRT), pulverized coal injection, use of oxygen, etc. (Aichinger et al. 2006).

2.3. The iron and steel industry in Mexico

Steel production in Mexico grew at 3.3% per year from 1990 to 2010, with important downturns in 2001 and 2008 associated with economic conditions. In 2010, the Mexican iron and steel industry produced 16.87 Mt of steel that accounted for 1.5% of the national gross domestic product and 8.4% of the manufacturing gross domestic product (INEGI 2012). Steel production using EAFs accounted for the 69.4% of the total crude steel production in Mexico in 2010; the remaining 30.6% was made in BOFs (INEGI 2012). Mexican iron and steel production consumed more energy than any other industrial use in the country in 2010, 197.25 petajoules (PJ), representing 14.3% of total final industrial energy consumption (SENER 2014). Most of the steel in Mexico is produced in medium-large facilities. Four major steel companies in Mexico produced 79.5% of the total crude steel manufactured in the country in 2010. These companies also represent 57% of the installed capacity, with plants ranging from 1 to 5.3 Mt/year (USGS 2011a).

2.4. The iron and steel industry in the U.S.

In the U.S., steel production peaked in 1973 at 137 Mt (USGS 2010a). After 2000, the level of U.S. steel production hovered below 100 Mt, with total production of 98 Mt in 2006. U.S. steel production dropped to 56 Mt in 2009, a 19 Mt decrease in one year (USGS 2010b), but rebounded to about 80 Mt in 2010 (worldsteel 2013). The CO_2 intensity and energy efficiency of U.S. steel production has continually improved because of industry restructuring during the

1970s and 1980s, an increase in production of steel in EAFs, adoption of continuous casting, use of direct hot rolling, and feedstock process improvements (Ruth et al. 2000, Tornell 1997).

3. Methodology

This study uses a bottom-up, physical-based methodology to compare the CO_2 intensity of crude steel production in China, Germany, Mexico, and the U.S. in 2010. The year 2010 was chosen to maximize the availability of comparable steel sector data. However, data published in these four countries are not always consistent in terms of analytical scope, conversion factors, and information on adoption of CO_2-abatement technologies, as we discuss below.

3.1. Boundary definitions

In this study, the boundary of the iron and steel industry is defined to include all of the following: coke making, pelletizing, sintering, iron making, steel making, steel casting, hot rolling, cold rolling, and processing such as galvanizing or coating (Figure 2). This boundary definition is used for calculating CO_2 emissions and CO_2 intensity in the four case study countries. This study takes net imported pig iron, direct-reduced iron (DRI), pellets, lime, oxygen, as well as ingots, blooms, billets, and slabs into account by adding the energy-related CO_2 emissions for production of these products to the total energy-related CO_2 emissions of the steel industry.

This study does not include CO_2 emissions of ferro-alloy production. Because ferro-alloy production is represented in overall steel industry energy statistics in China as a separate industry category (category 3240 within overall category 32), it was possible to subtract ferro-alloy contributions from the overall energy use for iron and steel production before we calculated CO_2 emissions. Similarly ferro-alloy production is reported separately in the U.S. *Manufacturing Energy Consumption Survey*, so energy consumed for this purpose is not included in U.S. iron and steel industry energy consumption value. In German statistics, ferro-alloy production is included in the iron and steelmaking processes; however, Germany mostly imports ferro-alloys from other countries, mainly China, India, and South Africa, so German ferro-alloy production is minimal, carried out by only one small company. Therefore, the influence of domestic ferro-alloy production on the CO_2 intensity in Germany is very small. In Mexico, ferro-alloy production is not reported separately. Appendix A explains how we estimated and subtracted the contribution of ferro-alloy production in Mexico.

There are a few special considerations associated with accounting for CO_2 emissions from coke production within the iron and steel industry. For China and the U.S., this analysis includes the total coal input used as a feedstock for coke making as well as coal used as fuel in other parts of the steel-making process. Only net imported coke (either produced in other domestic industries or imported from other countries) is included as a source of input energy to the iron and steel industry. Net imported coke is total imported coke minus total exported coke. The energy value of the coke produced in the coke-making process within the iron and steel industry and used in the iron-making process is not included because the coal initially used to produce the coke is already accounted for within the boundary definition of the entire industry. Because German statistics exclude coke ovens, we treat coke as an energy input for Germany and the energy used for its production is treated as a purchased energy carrier. This study does not count the coke trade that occurs within the boundary of the industry because the total coal input to the industry is already taken into account. This study accounts for net imported pig iron, DRI, pellets, lime, oxygen, as well as ingots, blooms, billets, and slabs by adding the energy-related CO_2 emissions for production of these products to the total CO_2 emissions associated with the energy input to the iron and steel industry. Because we do not have data for Germany on lime imported from outside of the boundary defined in this study, the contribution of imported lime to the CO_2 intensity of steel production in Germany is not included.

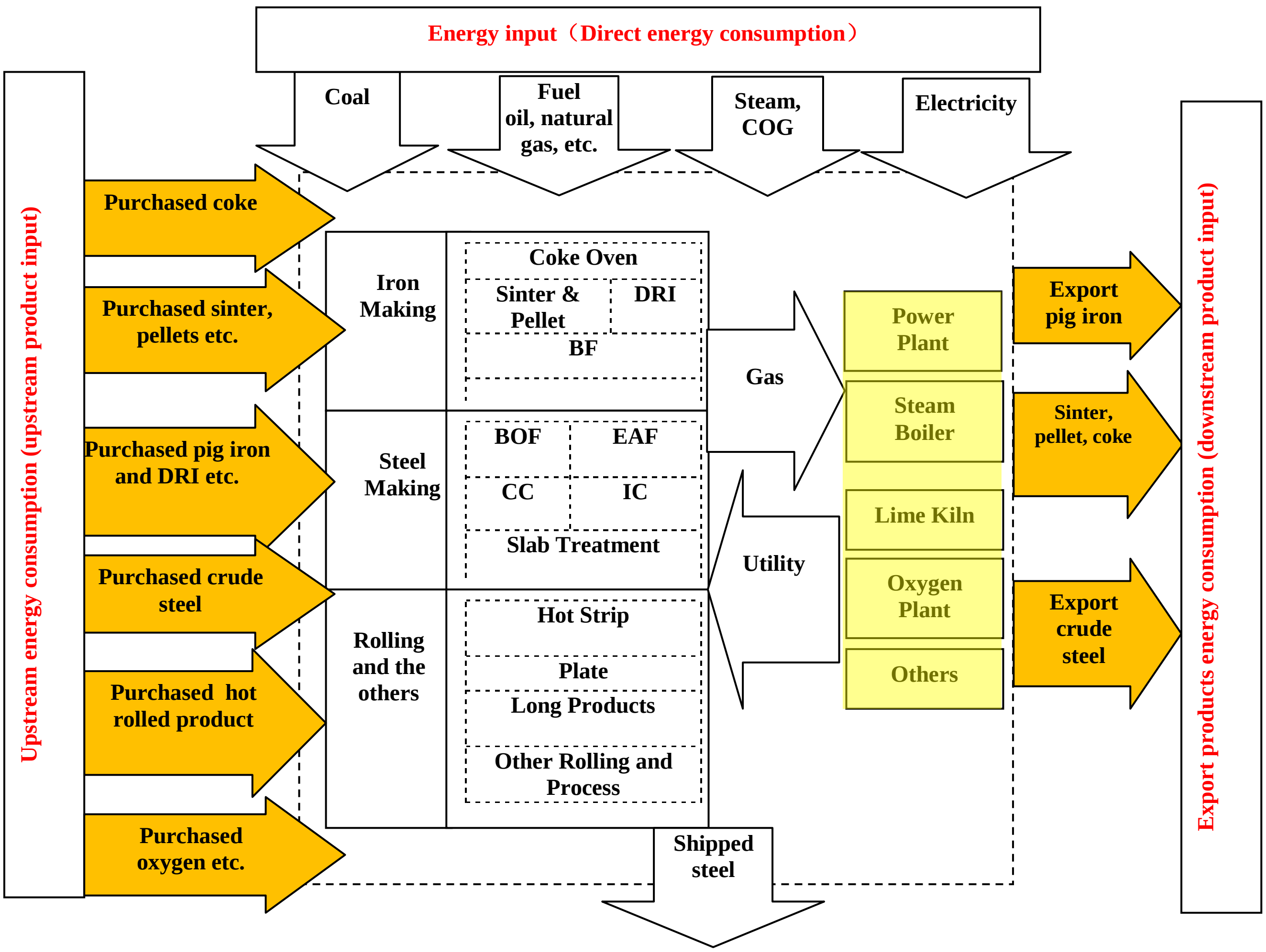

Figure 2. Flow chart of iron and steel sector boundaries used in this study
Note: BF: blast furnace; BOF: basic oxygen furnace; EAF: electric arc furnace; DRI: direct reduced iron; CC: continuous casting; IC: investment casting

In addition, this study does not include CO_2 emissions associated with other energy-intensive products manufactured for the iron and steel industry (e.g., electrodes, refractories, etc.). These products could be included in a more extensive, life-cycle analysis study of the industry but are excluded here because the focus of this study is on iron and steel production. This approach mirrors that taken by Stubbles (2000). The current study also does not take into account the embodied energy and CO_2 of the scrap used in the iron and steel industry or the CO_2 emissions associated with mining. Finally, the energy-related CO_2 emissions from further processing of steel by foundries are also excluded from this analysis.

3.2. Conversion factors

3.2.1. Fuel conversion factors

The country-specific net calorific value (NCV) conversion factors for different fuels for China, Germany, Mexico, and the U.S. were used to convert the physical quantities of fuels consumed to produce steel to energy values. In our previous analysis (Hasanbeigi et al. 2011), we developed a scenario in which we used the common International Energy Agency (IEA) NCVs of fuels for both countries to assess the effect of differences in country-specific NCVs of fuels on the energy-intensity results. We found that the effect is minimal and can be ignored. Therefore, in this report we do not develop a scenario using IEA NCVs for both countries instead of country-specific NCVs. Detailed information on country-specific NCV conversion factors for different fuels for China and the U.S. can be found in Hasanbeigi et al. (2011), for Germany in Arens et al. (2012), and for Mexico in SENER (2012).

3.2.2. Conversion factors for purchased fuels and auxiliary/intermediary products

For this study, international average energy conversion factors are used for products that are purchased externally and imported or exported by the iron and steel industry. This is done because imported products can come from different countries and thus vary in the energy consumed during their production as a result of country-specific differences in production technology and energy structure. The energy conversion factors for external products in this study are provided by the World Steel Association (worldsteel) (worldsteel n.d., worldsteel 2008b). We first calculate the embodied energy in terms of electricity and fuel use of the net imported auxiliary/intermediary products (in megajoules per kilogram [MJ/kg]), then we multiply the electricity and fuel consumption by the respective assumed country-specific CO_2 conversion factors to calculate the embodied energy-related CO_2 in these materials.

Table 1 gives the energy conversion factors for purchased fuels and materials as well as imported auxiliary/intermediary products along with the share of electricity used for production of each product. The values provided by worldsteel are assumed to be the international average and are used for the base case in this study. The results of the calculation based on worldsteel conversion factors might be slightly different from the steel-industry CO_2 intensity calculated for each country using exact conversion factors that take into account the countries origin of all the intermediary products and the CO_2 intensity of the products in those countries. However, that calculation was not undertaken for this study.

Table 1. Conversion factors for purchased fuels and auxiliary/intermediary products

	Coke [a]	Pig Iron [a]	Coal based DRI [a]	Gas based DRI [a]	Pellets [a]	Crude Steel [b]	Lime [a]	Oxygen [a]
	MJ/kg	MJ/kg	MJ/kg	MJ/kg	MJ/kg	MJ/kg	MJ/kg	kWh*/m^3
worldsteel factors (final energy)	3.7	19.8	17.0	13.4	2.1	16.5	4.1	0.7

[a] worldsteel n.d., [b] worldsteel 2008a *kilowatt-hours

For the fuel use of the net imported auxiliary/intermediary products, we calculated the weighted average fuel CO_2 emissions factor of the steel industry for each country, with a few exceptions as follows. For net imported coke, the CO_2 conversion factor of the coking coal was used to calculate the CO_2 emissions associated with the fuel use for producing the net imported coke. For the coal-based direct reduced iron (DRI), the CO_2 conversion factor of "other bituminous coal" was used. For the net imported DRI in the U.S. (the type of DRI was not specified), we based our approach on Chukwuleke et al. (2009) and assumed that 85% of the DRI imported to the U.S. is natural gas based and 15% is coal based. We applied these shares and used the CO_2 conversion factor of natural gas and other bituminous coal to calculate the CO_2 emissions associated with fuel used to produce the net imported DRI to the U.S. For the CO_2 emissions associated with the energy used for the rolling and finishing of imported ingots, blooms, billets, and slabs, we used the weighted average fuel CO_2 emission factor of the "Steel Products from Purchased Steel" industry (North American Industry Classification System [NAICS] category 3312) because the energy used for rolling and finishing of imported crude steel products is reported under this industry category in the U.S. statistics. For the CO_2 emissions associated with the energy used for net imported lime, we used the weighted average fuel CO_2 emission factor of the "Lime" industry (NAICS category 327410).

3.2.3. Carbon dioxide conversion factors

The fuel CO_2 conversion factors used for calculating CO_2 emissions from energy consumption were taken from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006). The fuel input to the steel industry reported in the statistics of each country was multiplied by the fuel CO_2 conversion factors to calculate the energy-related CO_2 emissions. Before these multiplications, the data were treated to conform to the boundary definition explained in Section 3.1. Table 2 shows the weighted average fuel CO_2 emissions factors used in this study for each country. Table 3 shows the national average grid electricity CO_2 emission factors used in our analysis for each country.

Table 2. Weighted average fuel CO_2 emissions factors for the steel industry in 2010

Item	CO_2 emission factor (kg CO_2/GJ)	Source of data used for the calculation
China weighted avg. fuel CO_2 emissions factor for the steel industry using China-specific fuel NCVs	101.07	NBS 2011; IPCC 2006
Germany weighted avg. fuel CO_2 emissions factor for the steel industry using Germany-specific fuel NCVs	93.14	UBA 2012a; IPCC 2006
Mexico weighted avg. fuel CO_2 emissions factor for the steel industry using Mexico-specific fuel NCVs	76.50	SENER 2012; IPCC 2006
U.S. weighted avg. fuel CO_2 emissions factor for the steel industry (NAICS category 331111) using Energy Information Administration (EIA) fuel NCVs	96.96	U.S DOE/EIA 2013a; IPCC 2006
U.S. weighted avg. fuel CO_2 emissions factor for "Steel Products from Purchased Steel" industry (NAICS category 3312) using EIA fuel NCVs	63.47	U.S DOE/EIA 2013a; IPCC 2006

Item	CO_2 emission factor (kg CO_2/GJ)	Source of data used for the calculation
U.S. weighted avg. fuel CO_2 emissions factor for the "Lime" industry (NAICS category 327410) using EIA fuel NCVs	89.65	U.S DOE/EIA 2013a; IPCC 2006

Table 3. National average grid electricity CO_2 emission factors in 2010

Country	Grid CO_2 emission factor (kgCO_2/kWh)	Sources of data used for the calculation
China	0.80	NBS 2011; IPCC 2006
Germany	0.54	UBA 2012b; IPCC 2006
Mexico	0.51	SENER 2012; IPCC 2006
U.S.	0.58	U.S. DOE/EIA 2012; IPCC 2006

3.3. Base year production, trade, and energy use data

3.3.1. Production and trade data

Table 4 through Table 7 list production, exports, and imports of pig iron, DRI, crude steel, and steel products in China, Germany, Mexico, and the U.S., respectively, for the year 2010.

Table 4. Production, imports, and exports of pig iron, DRI, crude steel, ingots, billets, and steel products in China, 2010 (Mt)

Product	Production	Exports	Imports	Net Imports	Used in industry
Hot metal/Pig Iron	595.60	0.71	0.87	0.16	595.77
DRI	0.03	0.21	1.38	1.17	1.20
Crude Steel	638.74	-	-	-	-
Ingots, Blooms, Billets, Slabs	-	42.70	17.11	-25.59	-

Source: EBCISIY 2011

Table 5. Production and trade of pig iron, DRI, crude steel, ingots, billets, and steel products in Germany, 2010 (Mt)

Product	Production	Exports	Imports	Net Imports	Used in industry
Sinter	26.79	0.0	16.39	16.39	43.18
Hot metal/Pig Iron	28.56	0.19	0.44	0.25	28.81
DRI	0.50	0.03	0.33	0.31	0.81
Crude Steel	43.83				
Ingots, Blooms, Billets, Slabs		2.34	1.78	- 0.56	

Source: WV Stahl 2013

Table 6. Production, imports, and exports of pig iron, DRI, crude steel, ingots, billets, and steel products in Mexico in 2010 (Mt)

Product	Production	Exports	Imports	Net Imports	Used in industry
Hot metal/Pig Iron	4.71	0.0	0.23	0.23	4.93
DRI	5.37	0.0	0.0	0.0	5.37
Crude Steel	16.87				
Ingots, Blooms, Billets, Slabs		1.41	0.32	-1.09	15.78

Source: INEGI 2012, SE 2012

Table 7. Production, imports, and exports of pig iron, DRI, crude steel, ingots, billets, and steel products in the U.S in 2010 (Mt)

Product	Production	Exports	Imports	Net Imports	Used in industry
Hot metal/Pig Iron	26.80	2.22	3.78	1.56	28.36
DRI	0.0	0.0	1.64	1.64	1.64
Crude Steel	80.50	-	-	-	-
Ingots, Blooms, Billets, Slabs	-	0.61	4.6	3.99	-

Source: USGS 2011b

For calculating energy intensities, we used crude steel production as the denominator. However, we note that the casting, rolling, and finishing processes that happen after the crude steel production are also within the boundary of the analysis.

3.3.2. Energy use and carbon dioxide emissions data

The energy consumption and associated CO_2 emissions of steel production were calculated according to the boundaries shown in Figure 2. Total energy use was adjusted for net trade in auxiliary and intermediate products. For a detailed explanation of energy data treatment and preparation for China and the U.S., see Hasanbeigi et al (2011). For an explanation of energy data for the German steel industry, see Appendix 1 and for Mexican steel industry, see Appendix 2. The energy consumption and CO_2 emissions of net imported coke, pig iron, DRI, steel ingots and billets, lime, oxygen, etc. for China, Germany, Mexico, and the U.S. are presented in Tables 8 -11.

Table 8. Total energy consumption and CO_2 emissions of China's steel industry production in 2010 based on study boundaries (net import is to the steel industry)

Component	**Electricity**		**Fuel**		**Total Final Energy**	
	Use (GWh)	**CO_2 Emissions (1,000t CO_2)**	**Use (TJ)***	**CO_2 Emissions (1,000t CO_2)**	**Use (TJ)**	**CO_2 Emissions (1,000t CO_2)**
Reported energy consumption *(excluding the energy use for production of intermediary products given below)*	271,900.00	216,432	10,674,171	1,078,787	11,653,011	1,295,219
Energy used for the production of purchased coke	8,473	6,745	715,713	67,706	746,216	74,451
Energy used for the production of net imports of hot metal/pig iron	27	21	3,186	322	3,281	343
Energy used for the production of net imports of coal-based DRI	160	128	19,246	1,821	19,823	1,948
Energy used for the production of net imports of steel ingots	7	6	674	68	700	74
Energy used for the production of net exports of steel billets/slabs	88	70	8,293	838	8,611	908
Total energy consumption of steel industry with embodied energy of net imported/exported auxiliary/intermediary products included	**280,655**	**223,402**	**11,421,282**	**1,149,542**	**12,431,642**	**1,372,944**

* terajoules

Note 1: The negative values indicate that the energy used by export products was subtracted.

Note 2: There are no energy use data given separately for lime and pellets because the energy use for the production of these products is included in the reported energy consumption of the steel industry in China (first row of this table), and there is no import or export of these two products.

Table 9. Total energy consumption and CO_2 emissions of Germany's steel industry production in 2010 based on study boundaries (net import is to the steel industry)

Component	Electricity		Fuel		Total Final Energy	
	Use (GWh)	**CO_2 Emissions (1,000t CO_2)**	**Use (TJ)***	**CO_2 Emissions (1,000t CO_2)**	**Use (TJ)**	**CO_2 Emissions (1,000t CO_2)**
Reported energy consumption *(excluding the energy use for production of intermediary products given below)*	14,881	8,096	640,431	58,848	694,004	66,944
Energy used for the production of purchased coke and coke breeze	485	264	38,434	4,112	40,179	4,376
Energy used for the production of purchased pellets	351	191	30,971	2,846	32,236	3,037
Energy used for the production of net imported pig iron	43	23	4,826	443	4,980	467
Energy used for the production of purchased DRI	35	19	3,982	366	4,110	385
Energy used for the production of purchased crude steel	-217	-118	-8,497	-781	-9,278	-899
Energy used for the production of purchased steam	-103	-56	-4,021	-369	-4,390	-425
Total energy consumption of steel industry with embodied energy of net imported/exported auxiliary/intermediary products included	**15,476**	**8,419**	**706,126**	**65,466**	**761,841**	**73,885**

* terajoules

Table 10. Total energy consumption and CO_2 emissions of Mexico's steel industry production in 2010 based on study boundaries (net import is to the steel industry)

Component	Electricity		Fuels		Total final energy	
	Use (GWh)	**CO_2 emissions (1000t CO_2)**	**Use (TJ)***	**CO_2 emissions (1000t CO_2)**	**Use (TJ)**	**CO_2 emissions (1000t CO_2)**
Reported energy consumption *(excluding the energy use for production of intermediary products given below)*	7,227	3,645	165,566	12,666	191,584	16,311
Energy use for the production of net imported coke	106	54	8,382	793	8,765	847
Energy use for the production of net imported pellets	0	0	10,335	791	10,335	791
Energy use for the production of net imported pig iron	39	20	4,347	333	4,486	352
Energy use for the production of net imported lime	24	12	1,336	120	1,422	132
Energy use for the production of net imported oxygen	417	211	0	0	1,503	211
Energy use for the production of net imported crude steel	-276	-139	-10,827	-828	-11,820	-968
Energy use for ferro-manganese manufacturing	-194	-98	-967	-74	-1,667	-172
Energy use for silico-manganese manufacturing	-538	-272	-2,436	-186	-4,372	-458
Total energy consumption with embodied energy of net imported/exported products included	**6,805**	**3,432**	**175,735**	**13,613**	**200,234**	**17,045**

* terajoules

Table 11. Total energy consumption and CO_2 emissions of U.S. steel industry production in 2010 based on study boundaries (net import is to the steel industry)

Component	Electricity		Fuel		Total Final Energy	
	Use (GWh)	CO_2 Emissions (1,000t CO_2)	Use (TJ)*	CO_2 Emissions (1,000t CO_2)	Use (TJ)	CO_2 Emissions (1,000t CO_2)
Energy use reported for the iron and steel industry in EIA *(excluding the energy use for production of intermediary products given below)*	50,360	29,161	941,110	91,246	1,122,406	120,406
Energy used for the production of net imported oxygen	4,131	2,392	0	0	14,872	2,392
Energy used for the production of net imported pig iron	686	397	28,417	2,755	30,888	3,153
Energy used for the production of net imported DRI	508	294	21,033	1,301	22,862	1,596
Energy used for the rolling and finishing of net imported ingots, blooms, billets, and slabs	5,270	3,052	7,385	469	26,357	3,520
Embodied energy of net imported ingots, blooms, billets, and slabs	3,968	2,298	51,486	4,992	65,772	7,290
Energy used for the production of net imported coke	662	383	19,269	1,823	21,651	2,206
Energy used for the production of net imported lime	297	172	6,063	544	7,133	716
Energy used for the production of net imported pellets	2,100	1,216	68,040	4,224	75,600	5,440
Total energy consumption of steel industry with embodied energy of net imported/exported auxiliary/intermediary products included	**67,982**	**39,365**	**1,142,804**	**107,353**	**1,387,541**	**146,718**

4. Results and discussion

In this study, we use CO_2 intensity as the index for comparison for the Chinese, German, Mexican, and U.S. iron and steel industries. We report the index of CO_2 emissions per tonne of crude steel produced, based on the industry boundary definition described in Section 3.1 and shown in Figure 2.

$$CO_2 \text{ intensity} = \frac{CO_2 \text{ emissions of iron and steel industry within the defined boundary}}{\text{Crude steel production within the boundary + Net trade of crude steel}}$$

The CO_2 intensity of steel production is influenced by a country's industry structure, technology, fuel choice, grid emissions factor, capacity utilization of steel plants, and materials (e.g., availability of scrap steel). We isolated the effects of some of these variables in factor analyses, two of which are presented in Section 4.1.

Figure 3 shows the CO_2 intensities for the iron and steel industry in China, Germany, Mexico, and the U.S. in the year 2010. Crude steel production in the U.S. in 2010 was 80.5 Mt. In addition, there were 3.99 Mt of net imported ingots, blooms, billets, and slabs. Thus, the total U.S. crude steel production used for the 2010 energy-intensity calculations was 84.49 Mt. Under the base-case analysis, as shown in Table 11 above, the CO_2 emissions associated with the total electricity and fuel consumption in the U.S. iron and steel industry in 2010, based on the industry boundary defined in Section 3.1, were 39,365 and 107,353 thousand t CO_2, respectively. If these emissions are divided by the production of crude steel given above, the CO_2 intensities related to the electricity and fuel use can be calculated separately. The sum of these two CO_2 intensities is given as the total CO_2 intensity of the U.S. steel industry. Figure 3 shows the results of the same calculation of CO_2 intensities for the steel industry in the other three countries studied.

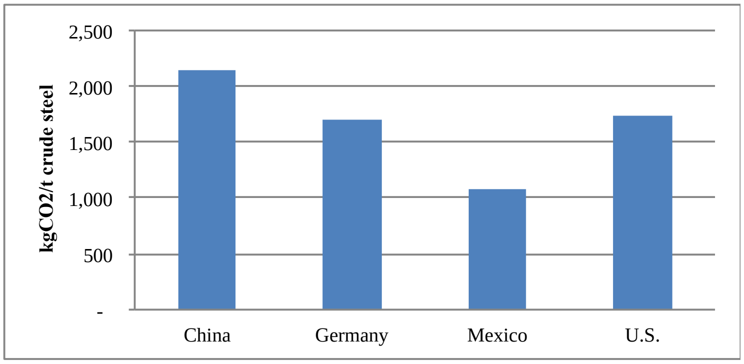

Figure 3. Base case - CO_2 intensity of the iron and steel industry in China, Germany, Mexico, and the U.S. in 2010

As can be seen from Figure 3, China has the highest and Mexico has the lowest total steel industry CO_2 intensity. The total CO_2 intensity of the Chinese steel industry is almost twice that of the Mexican steel industry. Two main reasons for low total CO_2 intensity in Mexico's steel industry are: 1) Mexico has the largest share of EAF steel production among the four countries studied (69.4% in 2010), and 2) Mexico's steel industry consumes a larger share of natural gas compared to that in other countries studied. This results in a lower average emissions factor for fuels in Mexico. Another interesting point to note is that the total CO_2 intensity of the German steel industry is 2% lower than that of the U.S. which is remarkable given that, in 2010, Germany had a lower share of EAF steel production (30.2% of total production) than the U.S. (61.3% of total production). EAF steel production has a much lower CO_2 intensity than BF/BOF steel production. Other factors influencing the CO_2 intensities in the four countries' steel industries are discussed in Section 4.1.

In addition to calculating CO_2 intensities for the entire steel industry, we calculated separately the CO_2 intensities associated with the EAF and BF/BOF production route in the four countries. Details about the calculation method for the energy intensities of EAF and BF/BOF production in China and the U.S. can be found in Hasanbeigi et al. (2011) and for Germany and Mexico in Appendices 1 and 2 of this report. Figure 4 shows the CO_2 intensities calculated for EAF and BF/BOF production in China, Germany, Mexico, and the U.S.

One of the main reasons that CO_2 intensity of EAF steel production in China is significantly higher than that in Germany and the U.S. is that more than 45% of the feed to EAFs in China in 2010 was pig iron (EBCISIY 2011). Pig iron is highly fuel and CO_2 intensive. In the U.S., only about 10% of the feed to EAFs is pig iron and in Germany the share of pig iron feed is minimal. As mentioned above, the prevalence of natural gas as a fuel for Mexico's EAFs is one reason that the CO_2 intensity of Mexico's EAFs is lowest (even marginally lower than Germany's); 98% of fossil fuel used in Mexico's EAF plants is natural gas, which has a lower emissions factor compared to that of coal and the other fossil fuels used in other countries. Other reasons are the relatively younger age and higher energy efficiency of Mexico's EAFs. The share of natural gas use in EAF plants is Germany is smaller than the share in Mexico. Mexico also has the lowest grid emissions factor, which helps to further reduce the CO_2 intensity of Mexico's EAFs.

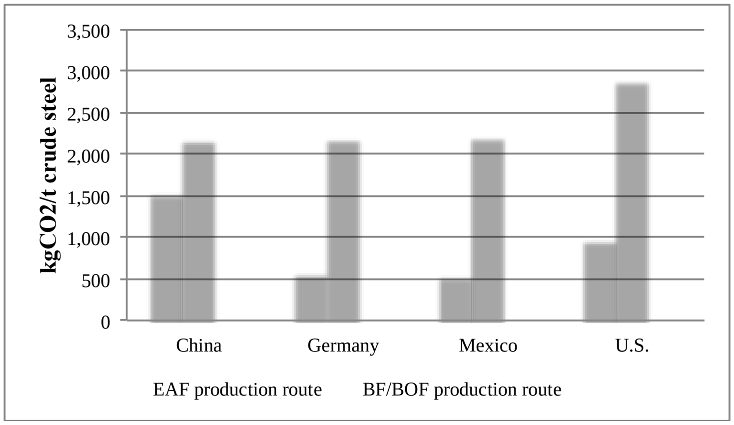

Figure 4. CO_2 intensities for EAF and BF/BOF production in China, Germany, Mexico, and the U.S. in 2010

Another noticeable result shown in Figure 4 is that the CO_2 emissions intensities of BF/BOF production route are quite similar in China, Germany and Mexico, but significantly higher in the U.S. The higher CO_2 emissions intensity of BOF/BOF route in the U.S. could be because of various reasons such as older BF/BOF plants and lower penetration of some major energy efficiency technologies such as coke dry quenching (CDQ) and top-pressure recovery turbine (TRT) in blast furnaces. However, detailed investigation of why BF/BOF steel production in the U.S. has significantly higher CO_2 emissions intensity can be the topic of future studies.

The intensities reported here are for the complete BF/BOF and EAF production routes, which includes casting, rolling, and finishing. That is, these intensity values for BF/BOF and EAF production include the energy use of net imported fuel and auxiliary and intermediary products, as discussed above and within the industry boundary defined for this study (Figure 2). Also, the CO_2 emissions intensities shown in Figures 3 and 4 might be different from CO_2 emissions intensities calculated in other studies for the steel industry in the four countries studied here. The primary reason for this difference could be the differences in the definition of what is included within the industry boundary and therefore what is or is not included in the calculation of intensity values. For example, if another study does not include the embodied energy of imported fuel and auxiliary/intermediary products, then the CO_2 intensity calculated in that study would likely be lower than the value calculated in this report.

4.1. Factor analyses

In addition to the base case presented above, we analyzed the impact of several different factors on the iron and steel production CO_2 intensity value for each country. The purpose of these factor analyses was to determine which variables are most important for explaining CO_2 intensity differences among China, Germany, Mexico, and the U.S.

The first factor analysis examines the impact on CO_2 intensity of a change in EAF ratio. This analysis has two sub-sections:

- 1.a. uses the country-specific fuel conversion factors, country-specific electricity grid CO_2 emissions factors, worldsteel conversion factors for auxiliary/intermediary products, and *China's* EAF ratio in 2010 to calculate CO_2 intensities for Germany, Mexico, and the U.S.
- 1.b. uses the country-specific fuel conversion factors, country-specific electricity grid CO_2 emissions factors, worldsteel conversion factors for auxiliary/intermediary products, and the *U.S.* EAF ratio in 2010 to calculate CO_2 intensities for China, Germany, and Mexico.

The second factor analysis examines the impact on CO_2 intensity of a change in electricity grid CO_2 emissions factors. It has two sub-sections as follows:

- 2.a. uses the country-specific fuel conversion factors, worldsteel conversion factors for auxiliary/intermediary products, and *China's* electricity grid CO_2 emissions factor in 2010 to calculate a CO_2 intensities for Germany, Mexico, and the U.S.
- 2.b. uses the country-specific fuel conversion factors, worldsteel conversion factors for auxiliary/intermediary products, and the *U.S.* electricity grid CO_2 emissions factor in 2010 to calculate CO_2 intensities for China, Germany, and Mexico.

Table 12 and Figure 5 show the results for the factor analyses of the four countries studied. This comparison presents the results of the base case and the two factor analyses, with the CO_2 intensities calculated for China, Germany, Mexico, and the U.S.

Table 12. Energy-related CO_2 intensities for the iron and steel industry in China, Germany, Mexico, and the U.S. (2010)

No.	Scenarios	Country	Total energy-related CO_2 intensity ($kgCO_2$/t crude steel)
Base	Country-specific NCVs for fuels Country-specific electricity CO_2 emissions factor worldsteel conversion factors aux/intermediary products	U.S. China Germany Mexico	1,736 2,148 1,708 1,080
1a	Country-specific NCVs for fuels Country-specific electricity CO_2 emissions factor worldsteel conversion factors aux/intermediary products China 2010 EAF ratio used for U.S.	U.S.	2,703
	(Base Scenario) Country-specific NCVs for fuels Country-specific electricity CO_2 emissions factor worldsteel conversion factors aux/intermediary products	China	2,148

No.	Scenarios	Country	Total energy-related CO_2 intensity (kgCO_2/t crude steel)
	Country-specific NCVs for fuels Country-specific electricity CO_2 emissions factor worldsteel conversion factors aux/intermediary products China 2010 EAF ratio used for Germany	Germany	2,036
	Country-specific NCVs for fuels Country-specific electricity CO_2 emissions factor worldsteel conversion factors aux/intermediary products China 2010 EAF ratio used for Mexico	Mexico	2,074
1b	(Base Scenario) Country-specific NCVs for fuels Country-specific electricity CO_2 emissions factor worldsteel conversion factors aux/intermediary products	U.S.	1,736
1b	Country-specific NCVs for fuels Country-specific electricity CO_2 emissions factor worldsteel conversion factors aux/intermediary products U.S. 2010 EAF ratio used for China	China	1,783
1b	Country-specific NCVs for fuels Country-specific electricity CO_2 conversion factors worldsteel conversion factors aux/intermediary products US 2010 EAF ratio used for Germany	Germany	1,200
1b	Country-specific NCVs for fuels Country-specific electricity CO_2 conversion factors worldsteel conversion factors aux/intermediary products US 2010 EAF ratio used for Mexico	Mexico	1,220
2a	Country-specific NCVs for fuels worldsteel conversion factors aux/intermediary products China electricity CO_2 emissions factor used for U.S. CO_2 intensity calculation	U.S.	1,911
2a	(Base Scenario) Country-specific NCVs for fuels Country-specific electricity CO_2 emissions factor worldsteel conversion factors aux/intermediary products	China	2,148
2a	Country-specific NCVs for fuels worldsteel conversion factors aux/intermediary products China electricity CO_2 emissions factor used for Germany CO_2 intensity calculation	Germany	1,798
2a	Country-specific NCVs for fuels worldsteel conversion factors aux/intermediary products China electricity CO_2 emissions factor used for Mexico CO_2 intensity calculation	Mexico	1,197
2b	(Base Scenario) Country-specific NCVs for fuels Country-specific electricity CO_2 emissions factor worldsteel conversion factors aux/intermediary products	U.S.	1,736
2b	Country-specific NCVs for fuels worldsteel conversion factors aux/intermediary products US electricity CO_2 emissions factor used for China CO_2 intensity calculation	China	2,052

No.	Scenarios	Country	Total energy-related CO_2 intensity (kgCO$_2$/t crude steel)
	Country-specific fuel conversion factors worldsteel conversion factors aux/intermediary products US electricity CO_2 emissions factor used for Germany CO_2 intensity calculation	Germany	1,720
	Country-specific fuel conversion factors worldsteel conversion factors aux/intermediary products US electricity CO_2 emissions factor used for Mexico CO_2 intensity calculation	Mexico	1,102

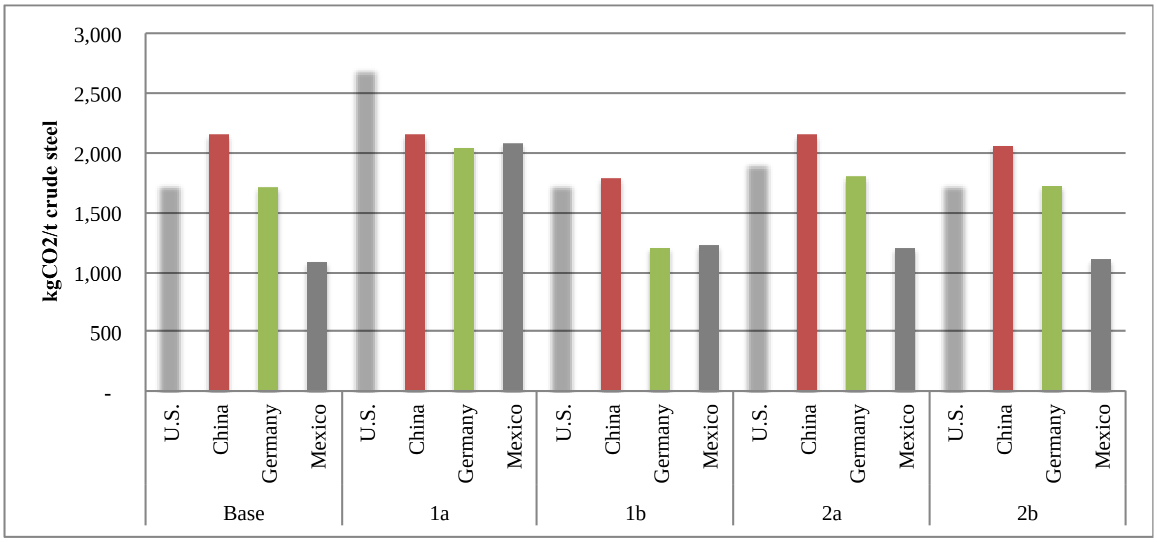

Figure 5. Comparison of CO_2 intensities for the iron and steel industry in China, Germany, Mexico, and the U.S.: Base case and four factor analysis results (2010)

Factor analysis 1a shows that when China's 2010 EAF ratio (which is the lowest of the EAF ratios among the countries studied) is used for CO_2 intensity calculations for the other three countries, the total CO_2 intensities of the German, Mexican, and U.S. steel industries increase by 19%, 92%, and 56%, respectively, compared to their base case analyses. The reason that the change in the CO_2 intensity is larger for Mexico than for Germany is the larger gap between the EAF ratio in Mexico in 2010 (69.4%) that was used for the base case analysis, and the EAF ratio in China in 2010 (9.8%) that is used for the calculation in factor analysis 1a. In this regard, the EAF ratio in Germany in 2010 (31.2%) is closer to China's EAF ratio.

The results of factor analyses 1a and 1b illustrate the strong impact of the EAF ratio on the CO_2 intensity of steel production in the countries studied. Therefore, in all industry-level comparison studies, this factor should always be taken into account and its effect evaluated.

Factor analysis 2a shows that when China's electricity grid CO_2 emissions factor in 2010 (which is the highest among those of the countries studied) is used for CO_2 intensity calculations in the other three countries, the total CO_2 intensities of the German, Mexican, and U.S. steel industries increase by 5%, 11%, and 10%, respectively, compared to their base case analyses. In the base case analysis, the CO_2 intensities associated with electricity use accounted for 11% and 27% of the total CO_2 intensity of the German and U.S. steel industries in 2010, respectively. This is also mainly because of a higher percentage of EAF steel production in the U.S. compared to that in Germany. Therefore, the increase in the CO_2 intensity as a result of rise in electricity grid CO_2 emissions factor is smaller for Germany and larger for the U.S. in this factor analysis.

On the other hand, factor analysis 2b shows that when U.S. electricity grid CO_2 emissions factor in 2010 is used for CO_2 intensity calculations in the other three countries, the total CO_2 intensities of the German and Mexican steel industries increase by 1% and 2%, respectively and in China decreased by 4% compared to their base case analyses. This is because electricity grid CO_2 emissions factor in Germany and Mexico is lower and in China is higher than that in the U.S.

Several uncertainties can influence the results and their interpretation. These include the calculation for the deduction of energy use for ferro-alloys from Chinese statistics (ferro-alloys are not within the boundary of this study, and how we addressed ferro-alloy energy use in the other three countries varies). For detailed discussion of the uncertainties for China and the U.S., please see Hasanbeigi et al. (2011). The uncertainties related to the calculation of CO_2 intensities for the steel industry in Germany and Mexico are discussed in Appendices 1 and 2 of this report.

4.2. Explanatory variables

As noted earlier, the purpose of the analysis presented in this report is to test a methodology for quantifying and comparing the CO_2 intensities of steel production in China, Germany, Mexico, and the U.S., using defined boundaries and conversion factors. This sub-section discusses seven variables that might explain why the steel industry's CO_2 intensity values differ among the four countries:

1) The share of EAF steel in total steel production
2) The age of steel manufacturing facilities in each country
3) The level of penetration of energy-efficient technologies
4) The scale of production equipment
5) The fuel shares in the iron and steel industry
6) The steel product mix in each country
7) Other factors

4.2.1 Structure of the steel industry and the share of EAF

The structure of the steel manufacturing sector is one of the key variables that explains the difference in CO_2 intensity values in China, Germany, Mexico, and the U.S. because EAF production uses significantly less energy to manufacture one tonne of steel. In 2010, the share of EAF production in total steel production was 9.8% in China, 30.2% in Germany, 69.4 in Mexico, and 61.3% in the U.S. The world average EAF production in 2010 was 29% (Figure 6).

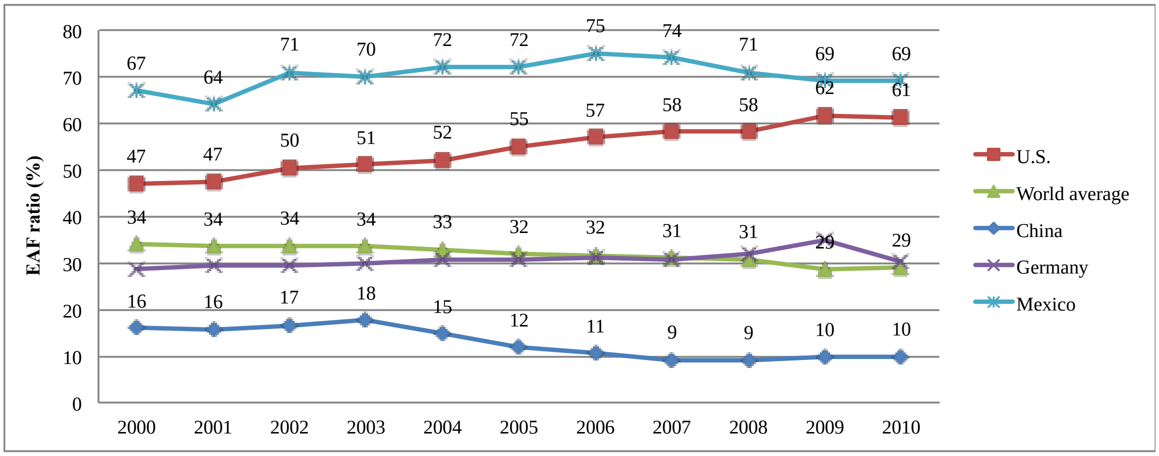

Figure 6. EAF share of total steel production in countries studied and world average values
Source: worldsteel 2011

Factor analysis 1 calculates the total CO_2 intensity for the German, Mexican, and the U.S. steel industries using the share of EAFs in China (1a); and the total CO_2 intensity for the Chinese, German, and Mexican steel industries using the share of EAFs in the U.S. (1b). Factor analysis 1a shows that when China's EAF ratio in 2010 is used for the CO_2 intensity calculation for the other three countries, the total CO_2 intensity of the steel industries in those countries increases significantly compared to their base case analyses. Factor analysis 1b shows that when U.S. EAF ratio in 2010 is used for the CO_2 intensity calculation of China, Germany, and Mexico's steel industries, the total CO_2 intensities of the Chinese, German, and Mexican steel industries decrease by 17% 30%, and 13% respectively, compared to their base case analyses.

The results of factor analysis 1a can be explained by the EAF ratio in these four countries, but in the results of factor analysis 1b we see that the decrease in the total CO_2 intensity of the German steel industry is larger than that of the Chinese steel industry even though the EAF ratio increases differ; the EAF ratio in Germany increases from 30.2% to 61.3%, and the EAF ratio in China increases from 9.8% to 61.3%. As can be seen in Figure 4, the reason for this is that the total CO_2 intensity for EAF steel production in China is approximately 1.6 times higher than the CO_2 intensity for EAF production in the U.S. One reason for this could be the larger share of pig iron used in EAFs in China compared to the makeup of EAF feed in the U.S. That is, in the U.S. in 2010, about 10% of EAF feed was pig iron. By contrast, more than 45% of the EAF feed in China was pig iron in 2010. Pig iron is produced in a BF and is highly fuel- and CO_2-intensive. Therefore, the higher the share of pig iron in the feed, the lower the electricity use in the EAF but the greater the total fuel used for EAF production of crude steel. The difference in percentage of pig-iron feed means that when we assume a larger share of EAF production in China's steel industry, this assumption does not reduce the total CO_2 intensity of the industry as much as the same assumption does in Germany. However, the significantly higher CO_2 intensity for EAF in China might not be entirely explained by the higher share of pig iron in the charge mix and requires further investigation.

4.2.2. Age of steel manufacturing facilities

As is evident in Figure 7, most of China's steel production capacity has been constructed since 2000. Annual production jumped from 129 Mt in 2000 to 627 Mt in 2010. During that same period, production in the U.S. dropped from 102 Mt to 80 Mt. In Germany, the iron and steel industry consolidated its plants, e.g., in 1991 there were 45 BF plants, and in 2010 this number had fallen to 18 (WV Stahl 2013). The total production of steel in Germany increased by only about 7% from 1990 to 2010 (Arens et al. 2012).

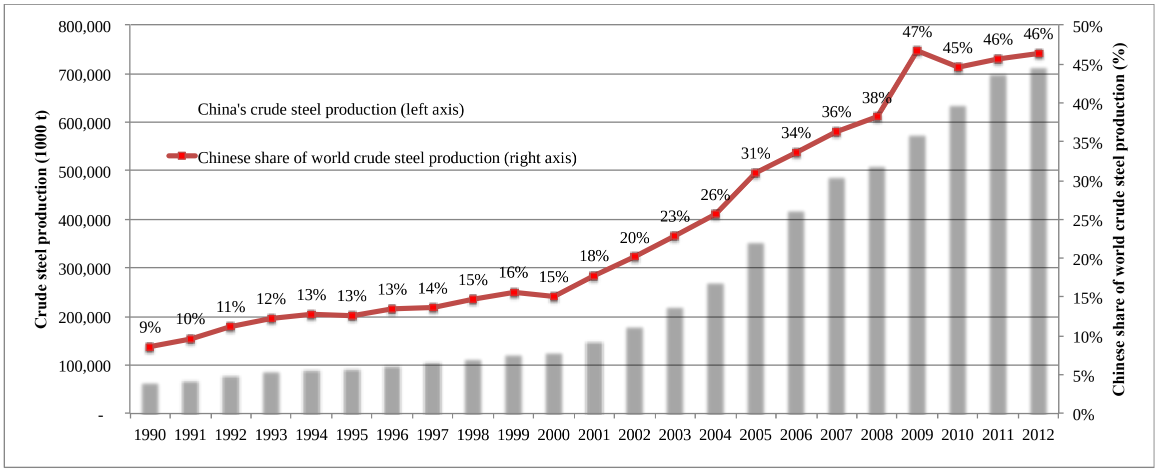

Figure 7. China's crude steel production and share of global production (1990-2010)
Source: worldsteel 2013

Although no data are available on the exact age of each steel enterprise in China, we can infer from the production data that in 2011 about 500 Mt of production (or about 80%) was from plants that were 10 years old or younger. In contrast, the average age of BOF vessels in the U.S. is 31.5 years (AIST 2010a), and the average age of EAFs in the U.S. is 30.9 years (AIST 2010b). Even though the U.S. vessels have been relined and other upgrades have been made, they are overall older than most of the steel production facilities in China and therefore could be less energy-efficient than the Chinese facilities At the same time, however, it should be noted that not all of the new Chinese plants have necessarily installed the most energy-efficient technologies.

In case of Mexico, the exact age of specific BOF and EAF plants is not known because the Mexican steel industry is continually carrying out facility modifications and modernizations, but, based on steel production information from INEGI (2012), we can assume that the older half of the installed BOF capacity in Mexico is approximately 30-37 years old, and the newer half is approximately 14-22 years old. Most of the EAF plants in Mexico were built between 1992 and 2000, with a second important increase in their number between 2003 and 2007 (INEGI 2012).

4.2.3. Fuel shares

The share of different fuels used in the iron and steel industry in the four countries studied is an important variable that influences the industry CO_2 intensity because some fuels are more carbon intensive than others.

The types of fuel used in this industry differ among the four countries. For example, in 2010, in the U.S. natural gas accounted for 32.4% of steel-industry's final energy use, but in China natural gas represented less than 1%. The dominant fuel used in China is coal, which is more carbon intensive than natural gas. In Germany, the key energy source is coke (and coke breeze), which accounted for more than 50% of total final energy consumption in 2010. Hard coal and natural gas made up approximately 20% and 15% of the German steel industry fuel mix, respectively, in 2010. In Mexico in 2010, natural gas accounted for 53% of steel industry final energy consumption, followed by coke with a 32% share (SENER 2014).

In addition to the share of fuels used directly in the iron and steel industry, the fuel mix for power generation in each country is also an important factor, especially when we compare the CO_2 emissions of the steel industry in the four countries. The fuel mix becomes even more important in light of the significant difference in the share of EAF steel production among the four countries. Because the share of EAF steel production in Mexico and the U.S. is much higher than in the other two countries, the share of steel-industry electricity use in total energy use is also higher in Mexico and the U.S. than in the other two countries. In this case, the fuel mix for power generation in the country, and as the result the emissions factor of the grid (kg CO_2/kilowatt-hour [kWh]), plays an important role when comparing the CO_2 emissions of the iron and steel industry in these countries. The effect of electricity grid CO_2 emissions factors is assessed in factor analysis 2, discussed above.

Overall, fossil fuels make up the majority of energy input in electricity generation in the four countries: more than 80% in China (the sum of coal, oil, and natural gas) (NBS 2011), around 50% in Germany (the sum of lignite, hard coal, and natural gas) (AG Energiebilanzen 2013), around 80% in Mexico (natural gas, heavy fuel oil, coal, and diesel) (SENER 2012), and around 70% in the U.S. (the sum of coal, natural gas, petroleum coking, and oil) (U.S. DOE/EIA 2012).

4.2.4. Steel products mix

Different steel products have different energy requirements in the rolling/casting/finishing processes. Therefore, the product mix is another key variable that should be considered when comparing CO_2 intensities among countries. Table 13 shows the differences in the production of some of iron and steel industry products in China, Germany, Mexico, and the U.S. in 2009[1].

4.2.5. Penetration of energy-efficient/carbon dioxide emissions reduction technologies

Data on penetration of energy-efficient and CO_2 emissions reduction technologies and practices in China, Germany, Mexico, and the U.S. are not fully comparable. The types of information available in these countries differs, so direct comparison of the penetration of certain technologies is not possible. One direct comparison that is possible is the penetration of EAFs, which was presented above. The application of energy-efficient and CO_2 emissions reduction technologies depends on factors such as raw materials used, energy sources, energy and operation costs, product mix, and the regulatory regime in the country.

[1] 2009 was the latest year for which the product mix data was available for all four countries.

Table 13. Product mix in iron and steel industry in China, Germany, Mexico, and the U.S. in 2009 (in thousand metric tonnes)

Steel Product	China	Germany	Mexico	U.S. [a]
Production of hot rolled long products (excluding seamless tubes)	332,506	10,229	6,468	16,081
Production of hot rolled flat products	307,717	18,812	5,938	37,863
Production of railway track material	5,478	241	-	902
Production of heavy sections (≥80mm)	9,458	1,637	326	3,763
Production of light sections (<80mm)	39,147	271	372	1,087
Production of concrete reinforcing bars	121,509	1,923	3,161	4,615
Production of hot rolled bars (other than concrete reinforcing bars)	55,393	1,268	425	3,099
Production of wire rod	96,728	5,160	2,184	1,493
Production of electrical sheet and strip	4,600	355	-	326
Production of tinmill products	-	-	96	2,016
Production of other metallic coated sheet and strip	20,693	5,871	1,148	9,677
Production of non-metallic coated sheet and strip	4,588	586	-	-
Total production of tubes and tube fittings	-	2,904	1,170	2,129

Source: worldsteel 2011

(a) deliveries; (b) total finished long products; (c) total flat products; (d) including light sections; (e) galvanized products only

Note: Since the 2010 data for Germany were incomplete, 2009 data are presented here for comparison.

A) Penetration of energy-efficient technologies and practices in China's iron and steel industry

With the rapid development of China's iron and steel industry, energy-efficient technologies and processes have also greatly improved. Penetration of equipment and technologies for waste-heat and waste-energy recycling has increased. The main technologies utilized include: coke dry quenching (CDQ) for the coking process, top-pressure recovery turbines (TRTs) for BFs, pulverized coal injection, and continuous casting. CDQ is a heat-recovery technology that produces electricity. Other technologies, such as low-temperature waste-heat recovery, are also gradually being adopted. The application and popularization of these energy-saving technologies have helped improve energy efficiency in the iron and steel industry. Many Chinese steel companies benefited from the Kyoto Protocol's Clean Development Mechanism (CDM) for additional funding to support CDQ and TRT projects in their plants.

1) Coke dry quenching and top-pressure recovery technologies in China

Figure 8 shows the penetration levels of CDQ and TRTs in China's iron and steel industry since the 1990s, showing a rapid increase in adoption in recent years. Both CDQ and TRTs save significant energy. For example, CDQ can recycle more than 80% of the sensible heat from heated coke. For each ton of coke quenched, this technology can recycle 0.45-0.6 tonnes of steam (at 4.5 megapascals) on average (Shangguan et al. 2009). The recycled steam can be fed directly into the streaming pipelines, or it can be used for power generation. In facilities using pure condensing steam turbines, on average 95-110 kWh of electricity can be generated from every ton of coke quenched.

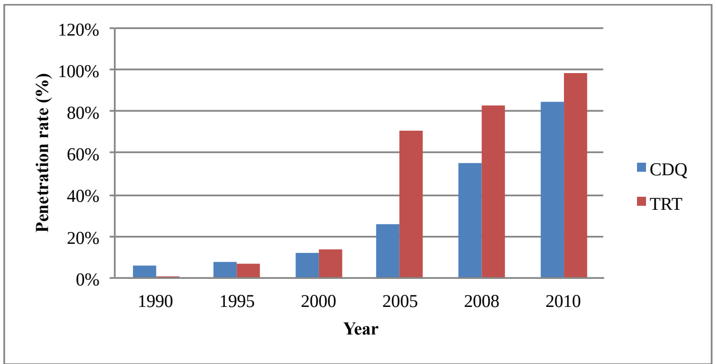

Figure 8. Use of CDQ and TRTs in key medium and large steel enterprises[2] in China
Sources: Hasanbeigi et al. 2011, CSM 2012-2013
Note: Penetration ratio of CDQ is the ratio at internal coking factories of steel mills.

TRTs can recycle large amounts of fuel to produce electricity without consuming any fuel. According to statistical reports, if operated under optimal conditions, TRTs can recycle 25-50 kWh per ton of hot metal, which can meet 30% of BF electricity demand. From 2000 to 2010, the number of BFs with TRTs in the Chinese steel plants increased from 33 to more than 400. By the end of 2007, all BFs with a capacity larger than 2,000 m^3 were equipped with TRTs, and 95% of the BFs with a capacity larger than 1,000 m^3 had TRTs.

In addition, all of the TRTs on BFs smaller than 1,000 m^3 utilized dry-dust removal. Some facilities with BFs larger than 1,000m^3 have also adopted this technology (e.g., the TRTs on two large BFs of 5,500 m^3 in Tangshan Steel Mill in Cao Pei Dian, China utilize dry-dust removal). TRTs with dry-dust removal can be 30-40% more efficient than TRTs with wet-dust removal and can produce 54kWh/t of hot metal (Shangguan et al., 2009; ECERTF 2008), which can meet approximately 30% of electricity demand for blast blowing. Considering the scale of China's iron and steel industry, the energy savings and CO_2 emissions reductions from both CDQ and TRT are significant.

2) Pulverized coal injection in China

Pulverized coal injection can reduce BF coke consumption, thereby reducing CO_2 emissions. Recently, the level of pulverized coal injection in the Chinese iron and steel industry has increased to 149 kg/t hot metal in 2010, which is comparable to higher levels in other countries (the world average is 125 kg/t hot metal), as shown in Figure 9.

[2] Medium and large enterprises have more than 300 employees and more than 30 million RMB annual sales revenue.

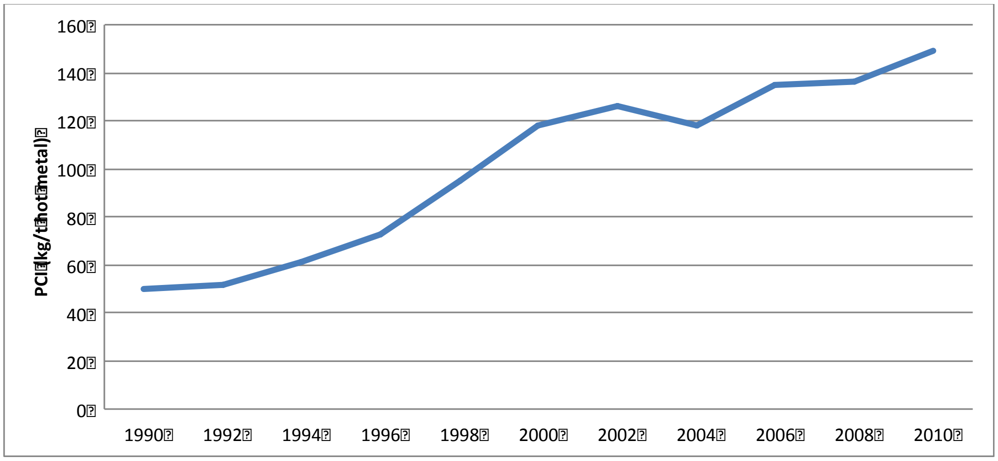

Figure 9. Pulverized coal injection in the Chinese steel industry, 1990-2010
Source: Yin 2009, CSM 2012-2013

3) *Continuous casting in China*
Continuous casting, in which molten steel is solidified into a semi-finished form such as a billet, bloom, or slab, saves energy compared to the use of stationary molds. Figure 10 shows the ratio of continuous casting in China from 1990 to 2010. The continuous casting ratio in China before 1995 was less than 50% but increased rapidly with the development of China's iron and steel industry, to 87% in 2000 and 99.8% in 2010. The increase in continuous casting has reduced energy use and CO_2 emissions from China's iron and steel industry.

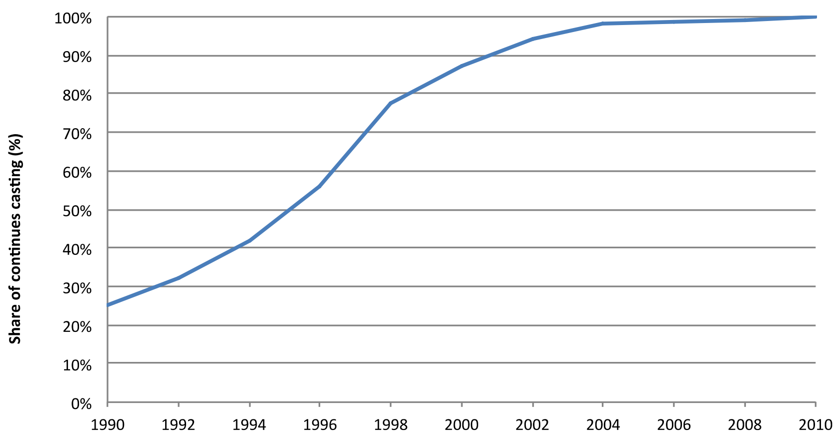

Figure 10. Share of continuous casting in Chinese steel production (1990-2010)
Source: Yin 2009, China MIPRI 2012

B) Penetration of energy-efficient technologies and practices in the German iron and steel industry

1) Coke dry quenching and top-pressure recovery technologies in Germany
CDQ is not used in Germany. The high investment cost and requirement for a back-up technology (wet quenching) make this technology economically viable only at high energy prices or with government and other financial incentives. Strict energy or environmental policies can

also increase the adoption rate of this technology. Chinese steel enterprises obtained support from the Clean Development Mechanism and from government financial incentives to implement this technology at a higher rate than has been seen in the U.S. or Germany.

TRTs were installed in ten BFs in Germany, and an additional three BFs that have adequate top pressure were not yet equipped with TRTs as of the publication of Plantfacts (2013).

2) Pulverized coal injection in Germany

Figure 11 shows the pulverized coal injection rate in Germany between 2002 and 2010. The low rate in 2009 is mainly due to the effects of the economic crisis. During the economic downturn, BFs and coke ovens had to reduce their production drastically without shutting down because of the time and cost involved in shutting down and restarting these facilities. Because more coke was produced than needed and because BFs need coke as a stabilizing element in the furnace, the minimum coke rate provided sufficient reducing agents, so additional coal was not needed. There is still further potential for pulverized coal injection in Germany; the highest reported rate is 177 kg coal/tonne hot metal, which show potential for improvement in other BFs in Germany. Detailed information on the injection of pulverized coal into BFs in Germany is available in Stahlinstitut VDEh (2010).

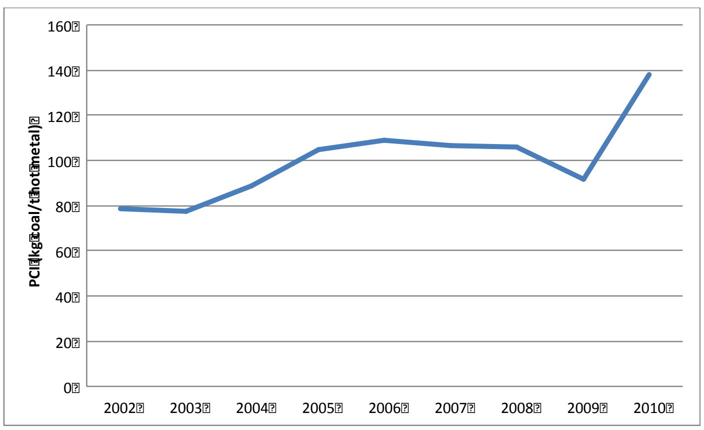

Figure 11. Pulverized coal injection rate in Germany between 2002 and 2010
Source: Stahlinstitut VDEh 2010

3) Continuous casting in Germany

Continuous casting was first introduced in Germany in 1964. After slow initial diffusion, it spread rapidly during the 1980s. Today, nearly all steel in Germany is produced by continuous casting. Figure 12 shows the penetration of continuous casting in the German steel industry between 1980 and 2008.

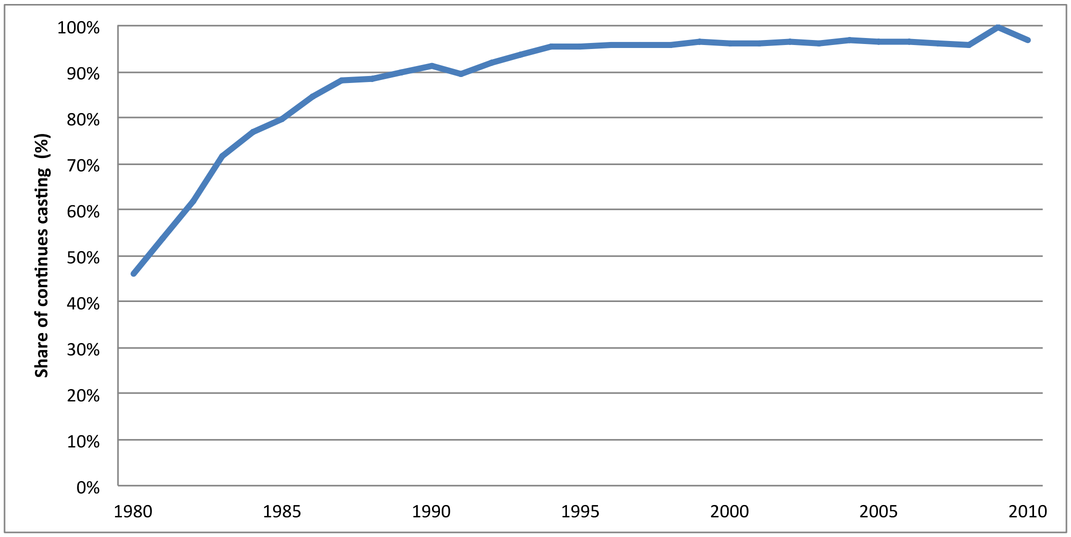

Figure 12. Penetration of continuous casting in Germany, 1980-2008
Source: WV Stahl 2013

C) *Penetration of energy-efficient technologies and practices in the Mexican iron and steel industry*

1) Continuous casting in Mexico

Since 2007, continuous casting has been used for 100% of steel production in Mexico. Figure 13 shows the evolution of the utilization of continuous casting in Mexico from 1970 to 2010.

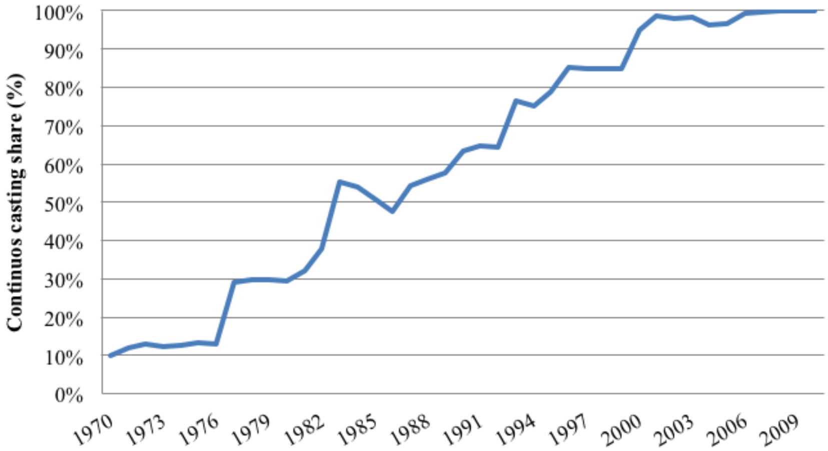

Figure 13. Continuous casting adoption rate as share of total steel production in Mexico, 1970 - 2010
Source: INEGI 2012

D) Penetration of energy-efficient technologies and practices in the U.S. iron and steel industry

We could not find information on the penetration of CDQ and TRT in the U.S. steel industry. However, information for other energy efficiency technologies and practices was available. For example, out of 348 establishments[3] in the U.S. iron and steel industry, only 16 used cogeneration technology in 2010[4] (U.S. DOE/EIA, 2013b). Also in 2010, 166 establishments reported using computer control for processes and major energy-using equipment, and 219 used adjustable-speed motors (U.S. DOE/EIA, 2013c). Table 14 shows energy management activities reported by U.S. iron and steel establishments in 2010.

Table 14. Energy management in U.S. iron and steel industry in 2010

Activity	# of plants [(a)]
Participation in one or more of the following types of activities	277
Energy audit or assessment	150
Electricity load control	125
Power factor correction or improvement	96
Equipment installation or retrofit for the primary purpose of using a different energy source (c)	29
Standby generation program	42
Special rate schedule (d)	128
Interval metering (e)	88
Equipment installation or retrofit for the primary purpose of improving energy efficiency affecting:	
Steam production/system (f)	36
Compressed air systems (g)	102
Direct/Indirect process heating	59
Direct process cooling, refrigeration	27
Direct machine drive (h)	107
Facility HVAC* (i)	76
Facility lighting	135

[a] This count includes only establishments that reported this activity in 2010 survey.
*heating, ventilation, and air conditioning
Source: U.S. DOE/EIA, 2013d

1) Continuous casting:

Figure 14 shows the ratio of continuous casting in the U.S., which had already reached a high level in the early1990s (about 76% in 1991), in contrast to the historical pattern in China.

[3] "Establishments" includes units that reported using any of the five energy-saving technologies listed by the Manufacturing Energy Consumption Survey at any time in 2006, plus units where usage of those technologies was not ascertained (U.S. DOE/EIA, 2013d).
[4] This count includes only establishments that reported cogeneration technology in use at any time in 2006 (U.S. DOE/EIA, 2013d).

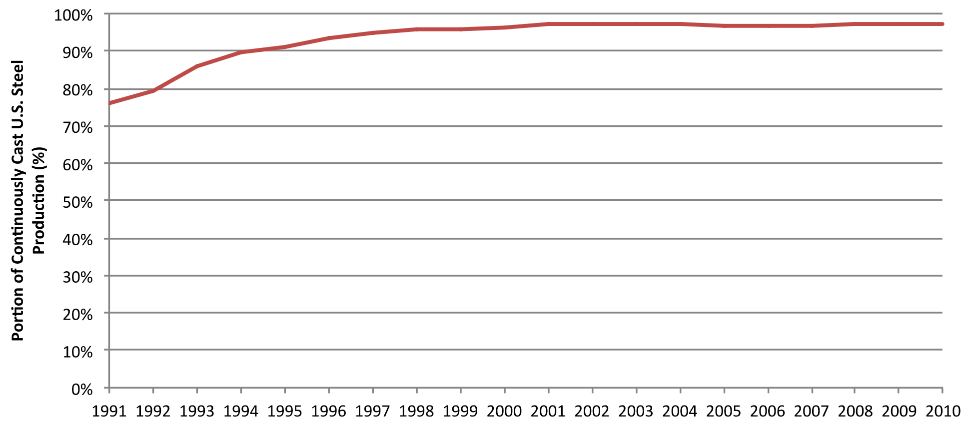

Figure 14. Percentage of continuously cast U.S. steel production (1991-2010)
Source: USGS 2010b.

Our analysis of the penetration and energy savings of energy-efficient and CO_2 emissions reduction technologies shows that each country exhibits its own characteristics in applying these technologies. In the U.S., there is more emphasis on energy management technologies whereas China has adopted more waste-heat/energy-recovery technologies. Germany has reduced BF energy consumption to such an extent – less than 500 kg of reducing agents (e.g., coke, coal, oil) per tonne hot metal (Stahlinstitut VDEh 2010) – that it is argued that no further dramatic BF improvements can be achieved in Germany. Options for further reduction in the overall energy efficiency of the German steel industry are heat recovery, energy management, and more efficient use of byproducts such as top gas.

4.2.6. Scale of Equipment

Overall, the Chinese iron and steel industry still has many small and inefficient enterprises and plants. There are many different types of steel enterprises in China, including large-scale integrated steel enterprises, independent rolling enterprises, and even independent iron-making enterprises. The total number of iron and steel enterprises in China is quite large, and it is almost impossible to obtain production and capacity information for every enterprise. However, production from medium and large enterprises represents 87% of the national crude steel production (554 Mt in 2010) (EBCISIY 2011), so these plants can represent the characteristics of major production equipment.

In 2006, China had 85 key medium and large enterprises with a total crude steel production of 349 Mt. The average annual production capacity of these enterprises was 4.1 Mt. China's average annual production capacity is greater than the U.S.'s. Since 2006, China has been implementing a policy focused on phasing out inefficient facilities in energy-intensive sectors. As a result, the overall efficiency of the Chinese iron and steel industry is increasing gradually. By the end of the 11th Five-Year Plan (2006-2010), China phased out 122 Mt of iron-making capacity and 70 Mt of steel-making capacity, surpassing the targets by 22% and 27%, respectively. In the current 12th Five-Year Plan, by the end of 2013, China phased out 17 Mt and 18 Mt of iron-making and steel-making capacity, respectively. The targets in the 12th Five-Year Plan are phasing out 48 Mt of iron-making and 48 Mt of steel-making capacity (MIIT 2015, 2013, 2012, 2010). A key issue in China is the large share of small BFs.

In Germany, the average annual hot metal production per BF was 1,900 Mt in 2010, which indicates that small BFs had been nearly phased out in Germany. Figure 15 shows the average hot metal production in BFs in Germany between 2002 and 2010. The significant decrease in average hot metal production in 2008 and 2009 was in response to the economic crisis during those years. Because it takes a long time and is costly to shut down and restart BFs, operators avoid shutting down for short periods and instead reduce production so that the BFs continue to work at less than full capacity. This reduces BF energy efficiency and productivity and increases overall energy and CO_2 intensities of steel production.

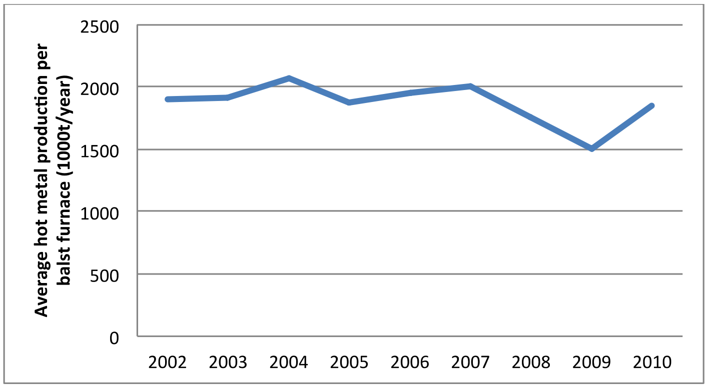

Figure 15. Average hot metal production per BF in Germany, 2002 - 2010
Source: Stahlinstitut VDEh 2010

The U.S. steel industry is characterized by consolidated, large-scale integrated steel producers and fragmented, mini-mill EAFs producers. Figure 16 illustrates the distribution of self-registered U.S. steel production facilities by annual capacity. The average capacity of integrated BOF plants in the U.S registry was 2.9 Mt per year in 2007; EAF plant average capacity was 0.93 Mt (AIST 2008).

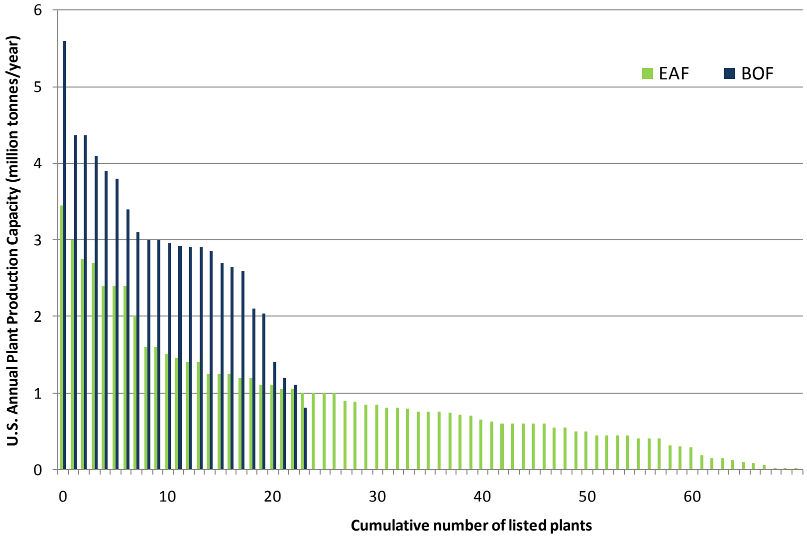

Figure 16. Distribution of registered US steel plants by production capacity (2007)
Source: AIST 2008

4.2.7. Other factors

Other factors that can influence the energy intensity and CO_2 emissions of steel production are:

- Capacity utilization of plants. Higher capacity utilization improves overall energy performance compared to lower capacity utilization if all other factors remain constant.
- Cost of energy and raw materials. Low-cost energy and raw materials are key components of managing costs in the steel industry. Changing energy and materials sources in order to optimize costs can affect the CO_2 and energy intensities of a plant.
- Differing environmental requirements from country to country. Environmental regulations affect industry CO_2 intensity. Operation of pollution control equipment requires energy, which adds CO_2 emissions.

5. Summary and conclusions

The goal of this study was to develop a methodology for accurately comparing the energy-related CO_2 emissions intensity of steel production in different countries. We applied the methodology to an analysis of energy and emissions intensity of the steel industry in China, Germany, Mexico, and the U.S. A key finding of this study is that the methodology must clearly define the industry boundaries (what materials and activities are and are not included) and the energy and CO_2 conversion factors used in the analysis because both elements have significant impact on the results. The boundary definition must address how to account for imported and exported inputs and intermediate products. Another key finding is that it is not possible to accurately compare the CO_2 intensity of steel production in different countries without performing multiple factor analyses. No single factor analysis can best compare all countries; each factor analysis highlights different issues affecting the accuracy and fairness of the comparisons. For example, for this comparison of the four countries studied, the results change significantly when the differences in production structure (i.e., the percentage of EAFs in each country) are taken into account in comparing the CO_2 intensity values.

This analysis shows that the structure of the steel industry heavily influences the CO_2 intensity and that if the German, Mexican, and U.S. steel industries were similar in structure to the Chinese steel industry (i.e., with the same EAF ratio – scenario 1a in our analysis), the CO_2 emissions intensity of steel production in Germany, Mexico, and the U.S. would increase by 19%, 92%, and 56%, respectively compared to their actual values (base case scenario). Another important factor is the national average grid electricity CO_2 emissions. Scenario 2a showed that if China's national average grid electricity CO_2 emissions factor was used for Germany, Mexico, and the U.S., the CO_2 emissions intensity of steel production in those three countries would increase by 5%, 11%, and 10%, respectively, compared to their actual values.

These examples demonstrate that it is important to perform multiple factor analyses to accurately identify the reasons for differences among calculated country-level CO_2 intensities. Only after the underlying reasons are understood can accurate comparisons be made among countries. Additional potentially important factors relevant to the industry and countries in this study could not be quantitatively analyzed because of scope limitations. Those were presented as explanatory variables and discussed qualitatively in this report.

One future research area related to this analysis is extending the current methodology to quantify other factors that influence the CO_2 intensity of steel production, especially the explanatory variables mentioned above. Another future research area involves extending this analysis to include other key steel-producing countries, such as Japan, India, and Brazil. A study with broader scope would offer policy makers additional insights into how to reduce domestic CO_2 intensity through analysis of differences in CO_2 intensity among other countries and the key variables that explain these differences.

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References

AG Energiebilanzen. 2013. www.ag-energiebilanzen.de (in German).

Aichinger, H.M., Steffen, R. 2006.Maßnahmen zur CO_2-Minderung bei der Stahlerzeugung. *Chemie Ingenieur Technik* 78 (4): 397-406. (in German).

Andersen, J.P., Hyman B. 2001. “Energy and material flow models for the US steel industry.” *Energy* 26(2) (February): 137-159.

Arens, M., Worrell, E., Schleich, J. 2012.“Energy intensity development of the German iron and steel industry between 1991 and 2007”. *Energy* 45:786e797.

Association for Iron and Steel Technology (AIST). 2010a. *2010 North American BOF Roundup. Iron & Steel Technology. November.*

AIST. 2010b. *2010 EAF Roundup*. Iron & Steel Technology. February.

AIST. 2008. *Directory of Iron and Steel Plants*. Warrendale PA: AIST.

China Metallurgical Industry Planning and Research Institute (MIPRI). 2012. "Eleventh Five-Year Plan" Steelmaking Technology Advances Review and Outlook (in Chinese). Available at http://www.steelplanning.cn/zyzxfw/ylyl/hyfx/lg/201211/t20121129_1057.html

Chinese society for metals (CSM). 2012-2013. *Report on Advances in Metallurgical Engineering and Technology*. Beijing, China. (in Chinese)

Chukwuleke, O.P. Cai, J.J. Chukwujekwu , S. Xiao, S. 2009. “Shift From Coke to Coal Using Direct Reduction Method and Challenges.” *Journal of Iron and Steel Research International* 16(2): 01-05.

Comision Reguladora de Energia (CRE). 2014. *Electricity generation and import permissions as of July 31st 2014*. http://www.cre.gob.mx/documento/1814.xlsx_(in Spanish)

Editorial Board of China Iron and Steel Industry Yearbook (EBCISIY). 2011. *China Iron and Steel Industry Yearbook*. Beijing, China (in Chinese).

EBCISIY. 2008. *China Iron and Steel Industry Yearbook*. Beijing, China (in Chinese).

Energy Conservation and Emissions Reduction Task Force of China Iron and Steel Industry Association (ECERTF). 2008. "Directions and Measures of Energy Conservation and Emission Reduction in China's Iron and Steel Industry". *China Iron and Steel Industry*, 2008, (10): 39-44 (in Chinese)

Farla, J., Blok, M. 2001. "The quality of energy intensity indicators for international comparison in the iron and steel industry." *Energy Policy* Volume 29, Issue 7, June 2001, Pages 523–543.

Hasanbeigi, A., Price, L., Aden, N., Zhang C., Li X., Shangguan F. 2011. *A Comparison of Iron and Steel Production Energy Use and Energy Intensity in China and the U.S.* Berkeley CA: Lawrence Berkeley National Laboratory Report LBNL-4836E.

Haque N., Norgate T. 2013. "Estimation of Greenhouse Gas Emissions from Ferroalloy Production Using Life Cycle Assessment with Particular Reference to Australia." *Journal of Cleaner Production* 39: 220–30.

Instituto Nacional de Estadistica y Geografía (INEGI). 2012. *La industria Sidergúrgica en México*. (in Spanish).

Intergovernmental Panel on Climate Change (IPCC). 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories; Reference Manual (Volume 2. Energy*), pp. 2-16. Retrieved on November 21, 2008 from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html

Kim, Y., Worrell, E. 2002. "International comparison of CO_2 emission trends in the iron and steel industry." *Energy Policy* 30 (10) (August): 827-838.

Kirschen M., Badr K., Pfeifer H. 2011. "Influence of direct reduced iron on the energy balance of the electric arc furnace in steel industry". *Energy* 36: 6146 – 6155.

Ministry of Industry and Information Technology (MIIT), 2015. *Surpassing the 2014 phasing out targets*. http://www.gov.cn/xinwen/2015-02/02/content_2813195.htm

MIIT, 2014. *Status of completing 2013 phasing out targets*. http://www.miit.gov.cn/n11293472/n11293832/n11293907/n16316572/16322104.html

MIIT. 2013. *Status of completing 2012 phasing out targets*. http://www.nea.gov.cn/2013-12/09/c_132953315.htm

MIIT. 2010. *Phasing Out Backward Capacities for 11th five year plan* (in Chinese).

National Bureau of Statistics (NBS). 2011. *China Energy Statistics Yearbook 2011*. Beijing: China Statistics Press.

Plantfacts. 2013. *Blast Furnaces. VDEh database*. Stahlinstitut VDEh. (in German).

Ruth M., Amato, A., Davidsdottir, B. 2000. "Impacts of Market-based Climate Change Policy on the US Iron and Steel Industry." *Energy Sources* 22 (3): 269 - 280.

Secretaría de Economía (SE). 2012. *Mexican Mining Statistical Yearbook 2012*.

Secretaría de Energía (SENER). 2012. *National Energy Balance of 2012*. (in Spanish).

SENER. 2014. *Prospectiva del Sector Eléctrico 2013-2027*. (in Spanish) .

Shangguan F.Q., Li X.P., and Zhang C.X. 2009. “Main Energy-Saving Measures in Iron and Steel Production and Analysis on Their CO2 Emission Reduction Potentials”. *Metallurgical Energy*, 2009, 28(1): 3-7 (in Chinese)

Stahlinstitut VDEh. 2010. *CO_2-Monitoring-Fortschrittsbericht der Stahlindustrie in Deutschland. Berichtsjahr 2010*. Düsseldorf, Germany. (in German).

Stubbles J. 2000. Energy Use in the U.S. Steel Industry: *A Historical Perspective and Future Opportunities.* U.S. Department of Energy, Office of Industrial Technologies, Washington, DC.

Tanaka, K. 2008. “Assessment of energy efficiency performance measures in industry and their application for policy.” *Energy Policy* 36: 2887-2902.

Tornell A. 1997. *Rational Atrophy: The US Steel Industry. Working Paper 6084*. Cambridge: National Bureau of Economic Research.

Umweltbundesamt (UBA), Deutsche Emissionshandelsstelle (DEHSt). 2012a. *Einheitliche Stoffwerte für Emissionsfaktoren, Heizwerte und Kohlenstoffgehalte für Brennstoffe*, Rohstoffe und Produkte. (in German).

Umweltbundesamt (UBA). 2012b. *Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix 1990-2010 und erste Schätzungen 2011*. (in German).

U.S. Department of Energy, Energy Information Administration (U.S. DOE/EIA). 2013a. Manufacturing Energy Consumption Survey (MECS)-2010 data (Table 1.2). Washington, DC: EIA. http://www.eia.doe.gov/emeu/mecs/mecs2006/2006tables.html

U.S. DOE/EIA. 2013b. Manufacturing Energy Consumption Survey (MECS)-2006 data (Table 8.3). Washington, DC: EIA. http://www.eia.doe.gov/emeu/mecs/mecs2006/2006tables.html

U.S. DOE/EIA. 2013c. Manufacturing Energy Consumption Survey (MECS)-2006 data (Table 8.2). Washington, DC: EIA. http://www.eia.doe.gov/emeu/mecs/mecs2006/2006tables.html

U.S. DOE/EIA. 2013d. Manufacturing Energy Consumption Survey (MECS)-2002 data (Table 8.1). Washington, DC: EIA. http://www.eia.doe.gov/emeu/mecs/mecs2006/2006tables.html

U.S. DOE/EIA. 2012. Electricity Data. (Tables on Generation by energy sources and Emissions). Washington, DC: EIA. http://www.eia.gov/electricity/data.cfm#generation

U.S. Geological Survey (USGS). 2011a. *Minerals commodity Summaries.* http://minerals.usgs.gov/minerals/pubs/mcs/2011/mcs2011.pdf

USGS. 2011b. *Minerals Yearbook- Iron and Steel 2010*. http://minerals.er.usgs.gov/minerals/pubs/commodity/iron_&_steel/myb1-2006-feste.pdf

USGS. 2010a. *Iron and Steel Mineral Commodity Summary.* http://minerals.usgs.gov/minerals/pubs/commodity/iron_&_steel/mcs-2010-feste.pdf.

USGS. 2010b. *Iron and Steel Statistics*. http://minerals.usgs.gov/ds/2005/140/ironsteel.pdf

Wirtschaftsvereinigung (WV) Stahl, Stahlinstitut VDEh. 2013. *Statistisches Jahrbuch der Stahlindustrie 2013/2014*. Düsseldorf, Germany. (in German).

World Steel Association (worldsteel). 2013. *Crude steel production, 1980-2012*. http://www.worldsteel.org/statistics/statistics-archive/annual-steel-archive.html

worldsteel. 2011. *Steel Statistical Yearbook 2011*. http://www.worldsteel.org/statistics/statistics-archive/yearbook-archive.html

worldsteel. 2008a. *Sustainability Report of the World Steel Industry*.

worldsteel. 2008b. *World Steel Sustainability Indicator Methodology*. http://www.worldsteel.org/pictures/storyfiles/SR08%20mthodology.pdf

worldsteel. n.d. *CO_2 Emissions Data Collection – User Guide, Version 6,* http://www.worldsteel.org/climatechange/files/2/2/Data%20collection%20user%20guide.pdf

Worrell E., Price L., Martin N., Farla J., Schaeffer R. 1997. "Energy intensity in the iron and steel industry: a comparison of physical and economic indicators," *Energy Policy* 25 (7) (June): 727-744.

Yin R. 2009. *Metallurgical* Process *Engineering (Version 2). Beijing: Metallurgy Industry Press.* (in Chinese)

Appendices

Appendix 1. Data preparation and analysis for Germany's steel industry

A.1.1. Energy-use data in Germany

The analyses for the German steel industry are based on data from the German Federal Statistical Office, which publishes annual iron and steel statistics. Energy consumption is reported in physical units, i.e. tonne for solid fossil and liquid fuels as well as steam; cubic meters for gases and oxygen; and kilowatt-hours for electricity. The following energy carriers are reported: coke, coke breeze, hard coal, natural gas, coke oven gas, oxygen, liquid fuels, other gases, BF gas, BOF gas, electricity, and steam. To each energy carrier, we assign a specific heating value and a specific CO_2 emissions factor. In the German steel statistics, all gases are reported as natural-gas equivalent, so the heating value used for all gases in the calculations is similar to that of natural gas. Coke ovens are not covered in the German iron and steel statistics, so in our calculation we treat coke and coke breeze as purchased energy carriers. Because steam and electricity are also produced in on-site facilities, we only treat net-imported steam and electricity as purchased energy carriers. Other purchased energy carriers include: pellets, sinter, direct reduced iron, pig iron and crude steel (i.e., ingots, blooms, billets, and slabs).

A.1.2. Energy and carbon dioxide intensity for electric arc furnace and blast furnace/basic oxygen furnace production in Germany

In German iron and steel statistics, energy consumption is not only reported by energy carriers but also by major industry processes. These processes include sinter and ore preparation, BF operations, EAF, BOF steelworks, rolling, on-site power plants, on-site steam generation, and other facilities. To calculate the CO_2 intensity for EAF-steel and BF/BOF steel, we assign a percentage of the processes to the two steel production processes (BF/BOF and EAF). Because all on-site power plants, sinter plants, BFs, and BOFs are located at integrated steel mills, their energy use and emissions are associated only with the BF/BOF production process. EAFs are assigned to the EAF steelmaking process. Steam-generation plants and other facilities are assigned to the BF/BOF route with the portion of 94% and 75%, respectively. The remainder is associated to EAF route. Energy use of rolling mills is allocated to BF/BOF and EAF process based on each production route's share of total crude steel production in Germany in 2010, i.e. 30.2% EAF steelmaking and 69.8% BF/BOF steelmaking.

A.1.3. Uncertainties in the calculation of carbon dioxide intensities for the German steel industry

Two uncertainties are associated with our calculation of the CO_2 intensity of German iron and steel production:

1. The data for our calculations are based on energy consumption provided in physical units. For each energy carrier we assumed a certain heating value to calculate the CO_2 intensity, and we used CO_2 conversion factors expressed in kg CO_2/GJ. The heating values for energy carriers can vary slightly across countries. For example, we assumed a country-specific heating value of 29.3 GJ/t for coal in Germany, while the International Energy

Agency (IEA) value is 28.2 GJ/t. Hasanbeigi et al. (2011) found that differences in fuel heating values have minimal impact on the results.

2. Another uncertainty is in the allocation of some sub-processes to the EAF and BF/BOF steelmaking production process. We assumed the following shares for the EAF route: steam generation 6%, rolling 31%, other facilities 25%. Although these assumptions pose some level of uncertainty in our analysis, we believe our detailed allocation of sub-processes to each production route makes our calculation of the CO_2 intensity of the two steelmaking routes fairly accurate.

Appendix 2. Data preparation and analysis for Mexico's steel industry

A.2.1. Energy-use data in Mexico

Energy consumption information for Mexico comes from energy balances (SENER 2012) and the Mexican energy regulatory commission (CRE 2014). It is important to mention that in Mexico, SENER reports the final energy consumption of the iron and steel industry as the energy used by the NAICS 3311 category "Iron and Steel Mills and Ferroalloy Manufacturing," with no further disaggregation (SENER 2012). Thus, to use the SENER statistics in our analysis, which excludes ferro-alloy manufacturing from the definition of the industry, we have to deduct the energy used to produce the ferro-alloys from the aggregate energy consumption reported by SENER. Because there are no previous studies or information about the energy use or intensity of ferro-alloy manufacturing in Mexico, we used final energy intensity values from a by Haque and Norgate (2013) along with data on the production of ferro-alloys (Table A.1).

Table A.1. Energy intensity for final energy use for ferro-alloys

Fuel	Ferro-manganese alloy	Silico-manganese alloy
Coke (GJ/t)	8.37	15.09
Coal (GJ/t)	3.57	3.02
Electricity (GJ/t)	8.64	14.40
Total (GJ/t)	20.58	32.51
Production (Mt)	81,019	134,471

Source: Haque and Norgate 2013, INEGI 2012

A.2.2. Energy and carbon dioxide intensity for electric arc furnace and blast furnace/basic oxygen furnace production in Mexico

Mexico's official energy data for iron and steel production (SENER 2012) are not disaggregated by production route. To address this issue, we calculated the energy intensities of the different production routes based on other previous studies by Kirschen et al. (2011) for 16 DRI- and scrap-based international EAF plants working under average conditions. The information from that study was adjusted to the Mexican case using our industry boundary definition.

Table A.2 shows the information obtained from Kirschen et al. (2011). The EAF operation parameters in the first column (inputs in physical units) represent the average of 16 international industrial EAFs, including furnaces of the Mexican steel manufacturer Ternium-Hylsa.

Table A.2. *EAF scrap-based and DRI-based materials usage ratios*

	Inputs in physical units	
	Scrap-based	**DRI-based**
DRI, t/tcs*	0	0.8
Lime, kg/tcs	34	60
Coal, kg/tcs	17	23
Oxygen, m^3/tcs	32	28
Nat gas, m^3/tcs	5	1.5
Electricity, kWh/tcs	391	570

*tcs: metric tons of crude steel

Source: Kirschen et al. 2011

Because there are no previous studies of BF/BOF process energy use in Mexico, we calculated the energy intensity of this process using the overall energy intensity and EAF intensity with the following equation:

$$EI_{BF/BOF} = \frac{EI_{CS} - \%EAF * EI_{EAF}}{\%BF/BOF}$$

Where:

$EI_{BF/BOF}$: final energy intensity of the BF/BOF production process in Mexico in 2010
EI_{CS}: final energy intensity of the overall iron and steel process
%EAF: share of crude steel produced by the EAF route in Mexico in 2010.
EI_{EAF}: final energy intensity of the EAF process in Mexico.
%BF/BOF: share of the crude steel produced by the BF/BOF production route in Mexico in 2010.

A.2.3. Uncertainties in the calculation of carbon dioxide intensities for Mexico's steel industry

Two main uncertainties associated with our calculations are:

First, the actual energy consumed in ferro-alloy manufacturing in Mexico might be different than we calculated because industry conditions vary. However, the possible error range does not have an important effect on our results because ferro-alloy manufacturing accounts only for about 3% of final energy use in Mexico.

Second, as mentioned above, Mexico does not collect the statistical information needed break down the energy consumption into the two steel production routes (BF-BOF and EAF); therefore, as explained, we took EAF energy and materials use data from a previous study by Kirschen et al. (2011). Another element of uncertainty is our CO_2 intensity estimation. Because there is no information on the energy consumption by production route, we assumed that EAF plants in Mexico use mostly natural gas as fuel for purposes of estimating fuel emissions by production route. This assumption was made due to the fact that there is no pig iron consumed in the EAFs in Mexico and that EAFs feedstocks were 45% DRI and 55% Scrap in 2010.